CHAPTER 2

THE *pn* JUNCTION

OUTLINE

OBJECTIVES

- Develop an understanding of the *pn* junction.
- Perform basic diode circuit analysis.
- Use the basic diode equation to determine the current through a diode.
- Investigate temperature effects on a *pn* junction.
- Develop a strong understanding of the forward- and reverse-bias operating modes of a diode.
- Recognize that a *pn* junction has a small parasitic capacitance.

2–1 INTRODUCTION

Semiconductor devices are the fundamental building blocks from which all types of useful electronic products are constructed—amplifiers, high-frequency communications equipment, power supplies, computers, and control systems, to name only a few. It is possible to learn how semiconductor devices can be connected to create useful products with little or no knowledge of the physics and theory of the device. However, the person who truly understands integrated circuit behavior has a greater knowledge of the capabilities and limitations of the device and is therefore able to use it in more innovative and efficient ways than the person who only has a functional understanding. Furthermore, it is often the case that the success or failure of a complex electronic system can be traced to a certain peculiarity or operating characteristic of a single device, and an intimate knowledge of how and why that device behaves the way it does is the key to reliable designs or to practical remedies for substandard performance.

This chapter introduces the reader to the *pn* junction. The *pn* junction is a fundamental building block that exists naturally in all integrated circuit structures. The diode, the result of a *pn* junction, is a very useful semiconductor device because it can control the direction of current flow—called *rectification*—in an electronic circuit. For practical purposes, current flows in the diode when it is on (forward bias), and no current flows when the diode is off (reverse bias). This chapter examines the basic operational characteristics of the *pn* junction and provides an introduction to basic diode concepts such as the diode current equation, current curve, threshold voltage, forward- and reverse-bias current behavior, junction capacitance, device types, ratings, and specifications. Some *pn* junctions, created by adjacent *p* and *n* regions, are unwanted parasitics that can affect the circuit's performance. This is addressed in greater detail in Chapters 17 and 18. Chapter 3 will introduce the reader to more advanced applications and analysis of diode circuits and devices.

Readers who wish to study the fundamental theory underlying the flow of charged particles through semiconductor material are encouraged to refer to

Appendix D, "Semiconductor Theory." The theory presented there includes numerous equations that allow us to compute and assign quantitative values to important atomic-level properties of semiconductors.

2–2 CREATING THE *pn* JUNCTION

Silicon (Si), the primary material currently used for manufacturing semiconductor devices, is a Group IVB element, which means that it contains four valence electrons. (The IVB identifies the location on the periodic table.) Germanium (Ge), used in special cases, is also a Group IVB element containing four valence electrons. These electrons, located in the outer shell, are loosely attached to the nucleus and can be easily altered through a process known as *doping*, which consists of adding impurities to intrinsic (pure) silicon to alter its electrical characteristics. These impurities are known as *dopant atoms*. The *p* or *n* material is created through doping processes such as ion implantation and diffusion. The *p*-type (positive) silicon material is created by doping intrinsic (pure) silicon (Si) with a dopant from a Group IIIB element such as boron (B). (The III indicates that the material contains three valence electrons.) The *n*-type (negative) silicon material is created by doping intrinsic silicon with a dopant from a Group VB element such as phosphorous (P). (The V indicates that the material contains five valence electrons.) A portion of the periodic table is shown in Figure 2–1.

Silicon, in its intrinsic or pure state, contains an equal concentration of protons (positive charges) and electrons (negative charges). (See Appendix D for a detailed examination of semiconductor theory.) The doping process alters this concentration and creates *extrinsic* or unpure material. When a covalent bond in semiconductor material is ruptured as in the doping process, a "hole" is left by the loss of an electron.

A dopant from Group IIIB is used to create the *p* regions. Doping the silicon with a Group IIIB element results in material with a greater concentration of *holes*. The increase in the concentration of holes yields a decrease in the *electron* concentration. The substitution of Group III for Group IV material results in material with one less electron in the outer shell. Hence, the material will be more positive. This *p*-type material is called *acceptor* material because of its ability to accept electrons.

A dopant from Group V is used to create *n* regions. Doping the silicon with a Group VB element results in material with a greater concentration of electrons and a decreased concentration of holes. A Group V substitution for Group IV results in material with one additional electron in the outer shell.

FIGURE 2–1 The portion of the periodic table containing the semiconductor elements

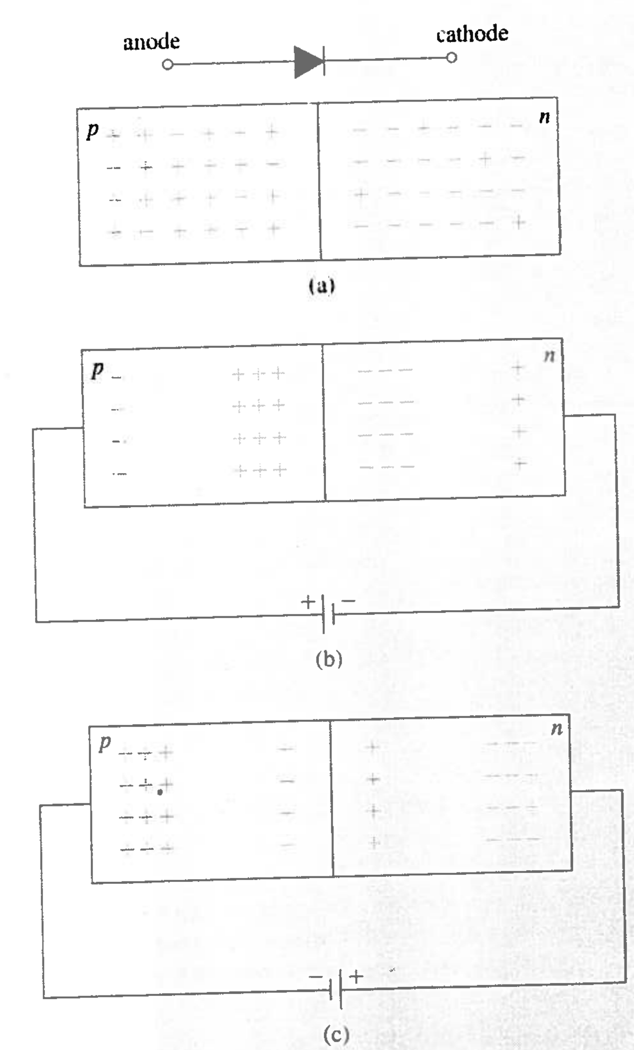
IIIB	IVB	VB
B Boron	C Carbon	N Nitrogen
Al Aluminum	Si Silicon	P Phosphorous
Ga Gallium	Ge Germanium	As Arsenic

Hence, the material will be more negative. The *n*-type material is called *donor* material because of its ability to donate electrons.

A *pn* silicon bar (a diode) and the schematic symbol for a diode are shown in Figure 2–2(a). The doped silicon bar is shown with adjoining *p* doped (*p*) and *n*-doped (*n*) regions. The *p* region is called the *anode* of the diode, and the *n* region is called the *cathode*. In Figure 2–2(b), the positive terminal of a battery is attached to the *p* region (anode); the negative lead of the battery is connected to the *n* region (cathode). This results in the diode being connected in the forward-biased mode and current will flow. Recall that the *p* region is full of holes (positive charges—majority carriers for the *p* material); therefore, the holes will be repelled by the positive terminal and pushed toward the *pn* junction. The *n* region is connected to the negative lead; therefore, the electrons (negative charges—majority carriers for the *n* material) will be repelled by the negative battery terminal and pushed toward the *pn* junction. If sufficient voltage is applied to the diode, the electrons and holes will jump across the junction in opposite directions.

In Figure 2–2(c), the *pn* junction is connected in the reverse-biased mode. In this case, the positive lead of the battery is connected to the *n* region, while the negative lead of the battery is connected to the *p* region. This pulls the majority carriers in the *p* (holes) and *n* (electrons) regions away from the

FIGURE 2–2 (a) The schematic symbol for a diode and the *pn* junction, (b) forward-biased *pn* junction, and (c) reverse-biased *pn* junction



junction leaving only the minority carriers at the junction, and essentially no current will flow. Recall that intrinsic silicon has equal concentrations of electrons and holes. When a region of the silicon is doped, this alters the n and p concentrations. The p region will have a heavy concentration of holes and a light concentration of electrons, while the n region will have a heavy concentration of electrons and a light concentration of holes.

2–3 BASIC DIODE OPERATION

A *discrete* diode is a single *pn* junction that has been fitted with an appropriate case (enclosure) and to which externally accessible leads have been attached. The leads allow us to make electrical connections to the anode (p) and cathode (n) sections of the diode. Semiconductor diodes are also formed inside *integrated circuits* as part(s) of larger, more complex networks and may or may not have leads that are accessible outside the package. (Integrated circuits have a large number of semiconductor components embedded and interconnected in a single wafer.)

In this section, we will investigate current and voltage relationships in circuits that contain diodes. We will learn how to analyze a circuit containing a diode as well as the behavior of the diode as a circuit element in considerable detail. A thorough analysis of this, the most fundamental building block in semiconductor electronics, is motivated by the following important facts:

1. The diode is an extremely useful device in its own right. It finds wide application in practical electronic circuits.
2. Many electronic devices that we will study later, such as transistors, contain *pn* junctions that behave like diodes. A solid understanding of diodes will help us understand and analyze these more complex devices.
3. A number of standard techniques used in the analysis of electronic circuits of all kinds will be introduced in the context of diode circuit analysis.

For a silicon diode, depending on small manufacturing variations and on the actual current flowing in it, the voltage drop is around 0.6 to 0.7 V. In practice, it is usually assumed to be 0.7 V. For *germanium* diodes, the drop is assumed to be 0.3 V. Therefore, for analysis purposes, we can replace the diode in a circuit by either a 0.7-V or a 0.3-V voltage source whenever the diode has a significant forward-biased current. Of course, the diode does not store energy and cannot produce current like a true voltage source, but the voltages and currents in the rest of a circuit containing the forward-biased diode are exactly the same as they would be if the diode were replaced by a voltage source. (The substitution theorem in network theory justifies this result.) Figure 2–3 illustrates these ideas.

In Figure 2–3(a), we assume that a forward-biased silicon diode has sufficient current to bias it and that it therefore has a voltage drop of 0.7 V. Using Ohm's law and Kirchhoff's voltage law, we can obtain

$$I = \frac{E - 0.7}{R} \tag{2-1}$$

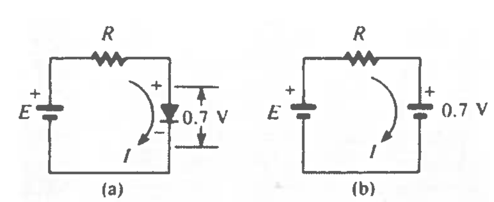


FIGURE 2–3 For analysis purposes, the forward-biased diode in (a) can be replaced by a voltage source, as in (b)

Figure 2–3(b) shows the equivalent circuit with the diode replaced by a 0.7-V source.

Our assumption that the voltage drop across the forward-biased diode is constant is usually accompanied by the additional assumption that the current through the diode is zero for all lesser voltages.

The idealized characteristic of the diode implies that it is an *open* circuit (infinite resistance, zero current) for all voltages less than 0.3 V or 0.7 V and becomes a short circuit (zero resistance) when one of those voltage values is reached. These approximations are quite valid in most real situations. Examples 2–1 to 2–3 examine basic diode circuit analysis.

EXAMPLE 2–1

Assume that a silicon diode is used in the circuit shown in Figure 2–4. Answer the following questions:

1. Is the diode forward or reverse biased?
2. What is the voltage drop across diode D_1?
3. Calculate the value of the current I in the circuit.

Solution

1. The anode of the diode is connected to the positive voltage terminal of the battery through the resistor R_1. The cathode of the diode is directly connected to the negative terminal of the battery. Therefore, the diode is forward biased.
2. The voltage drop across a forward-biased silicon (Si) diode is assumed to be 0.7 V.
3. Write the KVL for the circuit and solve for I.

$$12 - (1\text{k})I - 0.7 = 0$$
$$I = 11.3/1\text{k} = 11.3\ \text{mA}$$

EXAMPLE 2–2

Assume that a silicon diode is used in the circuit shown in Figure 2–5. Answer the following questions:

1. Is the diode forward or reverse biased?
2. What is the voltage drop across diode D_1?
3. Determine the value of the current I in the circuit.
4. How would the circuit analysis change if D_1 was changed to a germanium (Ge) diode?

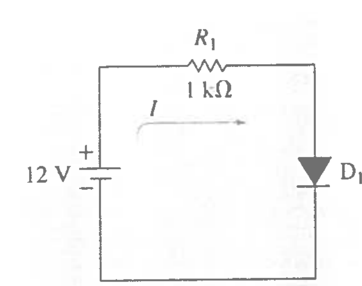


FIGURE 2–4 The circuit for Example 2–1

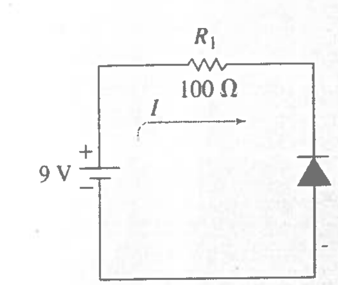


FIGURE 2–5 The circuit for Example 2–2

Solution

1. The anode of the diode is directly connected to the negative voltage terminal of the battery. The cathode of the diode is connected to the positive terminal of the battery through resistor R_1. Therefore, the diode is reverse biased.
2. In the reverse-bias mode, the diode can be approximated as an open circuit. This means that no current is flowing in the circuit and the voltage drop across R_1 is zero. The voltage across the diode is therefore 9.0 V.
3. Based on the answer to part 2, the current I is zero.
4. A forward-biased Ge diode has a voltage drop of 0.3 V but diode D_1 is reverse biased. The diode is still open and the value of the current I is zero.

EXAMPLE 2-3

In this example, diodes D_1 and D_2 are connected in series, as shown in Figure 2-6. Assume that D_1 and D_2 are silicon (Si) diodes. Answer the following questions:

1. Are the diodes forward or reverse biased?
2. Determine the value of the current I in the circuit.
3. What is the value of the voltage measured from point A to point B, V_{AB}?

Solution

1. The anode of diode D_1 is connected to the positive terminal of the battery through resistor R_1. The cathode of diode D_1 is connected to the cathode of diode D_2 while the anode of D_2 is directly connected to the negative terminal of the battery. For a diode to be forward biased, the anode lead of the diode must be more positive than the cathode lead. It can be seen that D_2 could never be forward biased since its anode lead is connected to the most negative point in the circuit. Therefore, diodes D_1 and D_2 are reverse biased (no current will flow).
2. In the reverse-bias mode, the diode is approximated by an open circuit. This means that no current is flowing in the circuit.
3. Because no current is flowing in the circuit, the voltage drop across R_1 will be zero. This means that the voltage at points A and B equals the voltage across the battery terminals. Therefore, the measured voltage V_{AB} is 6.0 V.

2-4 THE DIODE CURRENT EQUATION

A common application of a *pn* junction is in the construction of a *diode*. The relationship between the voltage across a *pn* junction and the current through it is given by the so-called diode equation:

$$I_D = I_s(e^{V_D/\eta V_T} - 1) \tag{2-2}$$

FIGURE 2-6 The circuit for Example 2-3

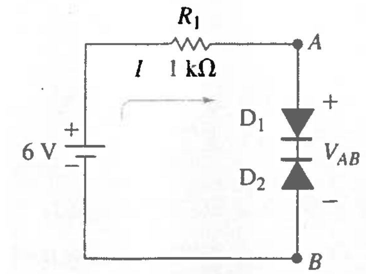
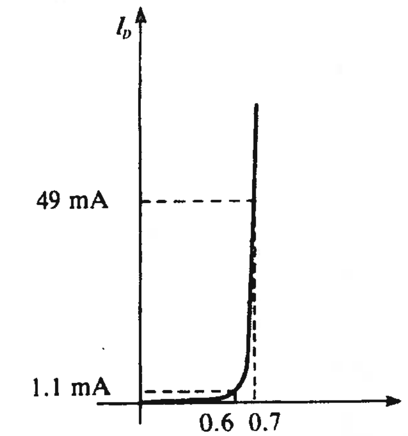


FIGURE 2-7 Current versus voltage in a typical forward-biased silicon junction. I_s = 0.1 pA



V_D	I_D
0	0
0.01	0.02 pA
0.05	0.16 pA
0.1	0.58 pA
0.2	4.58 pA
0.3	31.9 pA
0.4	219 pA
0.5	22 μA
0.6	1.1 mA
0.7	49 mA

where I_D = diode current, A
V_D = diode voltage, V (positive, for forward bias)
I_s = *saturation* current, A
η = *emission coefficient* (a function of V_D whose value depends also on the material; $1 \le \eta \le 2$)

$$V_T = \text{thermal voltage} = \frac{kT}{q} = \frac{[1.38 \times 10^{-23}][273 + T(°C)]}{1.6 \times 10^{-19}} = \frac{T}{11,600}$$

where k (Boltzmann constant) = 1.38×10^{-23} J/°K
T (Kelvin) = 273 + T(°C); C (degrees centigrade)
q (charge of an electron) = 1.6×10^{-19} C; C (coulombs)

Equation 2-2 reveals some important facts about the nature of a forward-biased junction. The value of V_T at room temperature is about 0.026 V. The value of η for silicon is usually assumed to be 1 for $V_D \ge 0.5$ V and to approach 2 as V_D approaches 0. So when V_D is greater than $2V_T$, or about 0.05 V, the term $(e^{V_D/\eta V_T})$ begins to increase quite rapidly with increasing V_D. For $V_D > 0.2$, the exponential is much greater than 1. Consequently, equation 2-2 shows that the current I_D in a silicon *pn* junction increases dramatically once the forward-biasing voltage exceeds 200 mV or so. The *saturation current* I_s, in equation 2-2 is typically a very small quantity (we will have more to say about it when we discuss *reverse* biasing), but the fact that I_s is multiplied by the exponential $(e^{V_D/\eta V_T})$ means that I_D itself can become very large very quickly. For V_D > 0.2 V, $I_D \approx I_s e^{V_D/V_T}$ and $V_D \approx V_T \ln \frac{I_D}{I_s}$. Figure 2-7 shows a plot of I versus V for a typical forward-biased silicon junction. Note the rapid increase in the current I_D that is revealed by the plot and the accompanying table of values. For this figure we assumed that I_s = 0.1 pA (= 10^{-13} A). Examples 2-4 and 2-5 examine more advanced diode circuit analysis.

Example 2-4 provides an example of using the diode equation (equation 2-2) to calculate the current through the diode when the exact value of the voltage drop across the diode is not known. This requires the use of an iterative process where the voltage across the diode must be guessed initially.

EXAMPLE 2-4

The silicon diode in the circuit shown in Figure 2-8 has a saturation current $I_s = 3 \times 10^{-14}$ A. Determine the current through and the voltage across the diode D_1. The temperature is 55°C. Assume η = 1.

Solution

Step 1. Diode D_1 is forward biased; therefore, assume that $V_D = 0.7$ V. The current I flowing through D_1 will be

$$I = (2 - 0.7)/3\ \text{k} = 0.433\ \text{mA}$$

Step 2. With this estimated current value of 0.433 mA, which is based on a guess of the voltage drop across D_1, we can calculate a more accurate diode voltage drop using the form

$$V_D \approx V_T \ln \frac{I_D}{I_s}$$

where $V_T = \dfrac{T}{11{,}600} = \dfrac{273 + 55}{11{,}600} = 28.3$ mV

$$V_D = V_T \ln(I_D/I_s) = (28.3\ \text{mV})\ln(0.433\ \text{mA}/3 \times 10^{-14}\text{A}) = 0.662\ \text{V}$$

Step 3. Through an iterative process, a new current value for I can be calculated using the voltage value calculated in step 2.

$$I = (2 - 0.662)/3\ \text{k} = 0.446\ \text{mA}$$

Step 4. Calculate a new value for V_D.

$$V_D = (28.3\ \text{mV})\ln(0.466\ \text{mA}/3 \times 10^{-14}\ \text{A}) = 0.662\ \text{V}$$

This equals the value calculated in step 2, which means that the iterative process is complete and that the voltage converged to a solution very quickly.

Example 2–5 demonstrates a technique for calculating the actual voltage drop across a set of parallel diodes when each diode has a different value for I_s.

EXAMPLE 2–5

Diodes D_1 and D_2 in Figure 2–9 have saturation currents $I_{s1} = 2 \times 10^{-14}$A and $I_{s2} = 5 \times 10^{-14}$ A. Assuming room temperature, determine the current through and the voltage across each diode.

Solution

Because the diodes are connected in parallel, their voltages will be the same. Let us assume a diode voltage drop of 0.6 V since, by inspection, the current could be small. The current I will be $I = (3 - 0.6)/1\ \text{k} = 2.4\ \text{mA} = I_{D1} + I_{D2}$. In

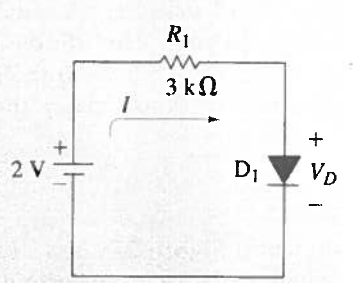


FIGURE 2–8 The circuit for Example 2–4

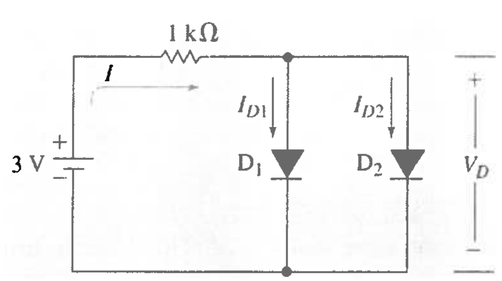


FIGURE 2–9 The circuit for Example 2–5

order to determine the current flowing through each device, equate their voltage, $V_T\ln(I_{D1}/I_{s1}) = V_T\ln(I_{D2}/I_{s2})$, and obtain $I_{D1} = I_{D2}(I_{s1}/I_{s2})$. But $I_{D1} =$ 2.4 mA $- I_{D2}$; substituting I_{D1} we can write

$$2.4\ \text{mA} - I_{D2} = I_{D2}\,(2/5)$$

or

$$I_{D2} = (2.4\ \text{mA})/1.4 = 1.714\ \text{mA}$$

and

$$I_{D1} = 2.4 - 1.714 = 0.686\ \text{mA}$$

With either of these two currents we can calculate a more approximated value for the voltage drop. Using I_{D2}, we obtain $V_D = 0.026\ \ln(1.714\ \text{mA}/5 \times 10^{-14}\ \text{A}) = 0.631$ V. The reader can verify that using I_{D1} yields the same result. With this new value for V_D, the current I can be recalculated as $I = (3 - 0.631)/1\ \text{k} = 2.369$ mA. Iterating I_{D2} as well, we obtain $I_{D2} = 2.369 - 1.692 = 0.677$ mA. If we do one more iteration, V_D will turn out to be 0.630 V and $I = 2.370$ mA. Even if we had started with $V_D = 0.7$ V, we would have seen that the diode voltage converges with one or at most two iterations.

Suppose now that the connections between the *pn* junction and the external voltage source are reversed, so that the positive terminal of the source is connected to the *n* side of the junction and the negative terminal is connected to the *p* side. This connection *reverse biases* the junction and is illustrated in Figure 2–10.

The polarity of the bias voltage in this case *reinforces*, or strengthens, the internal barrier field at the junction. Consequently, diffusion current is inhibited to an even greater extent than it was with no bias applied. The increased field intensity must be supported by an increase in the number of ionized donor and acceptor atoms, so the depletion region widens under reverse bias.

The unbiased *pn* junction has a component of drift current (see Appendix D) consisting of minority carriers that cross the junction from the *p* to the *n* side. This reverse current is the direct result of the electric field across the depletion region. Because a reverse-biasing voltage increases the magnitude of that field, we can expect the reverse current to increase correspondingly. This is indeed the case. However, because the current is due to the flow of minority carriers only, its magnitude is very much smaller than the current that flows under forward bias (the forward current).

It is this distinction between the ways a *pn* junction reacts to bias voltage—very little current flow when it is reverse biased and substantial

FIGURE 2–10 A voltage source V connected to a reverse-bias *pn* junction. The depletion region (shown shaded) is widened

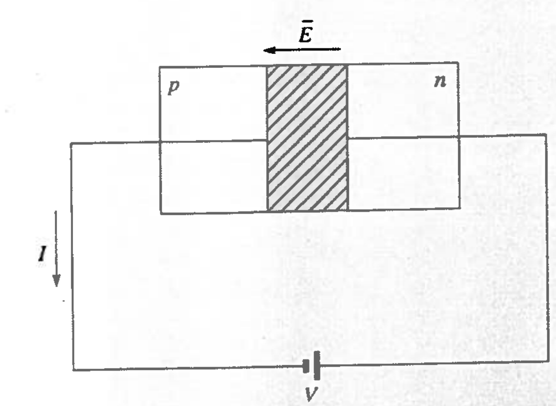
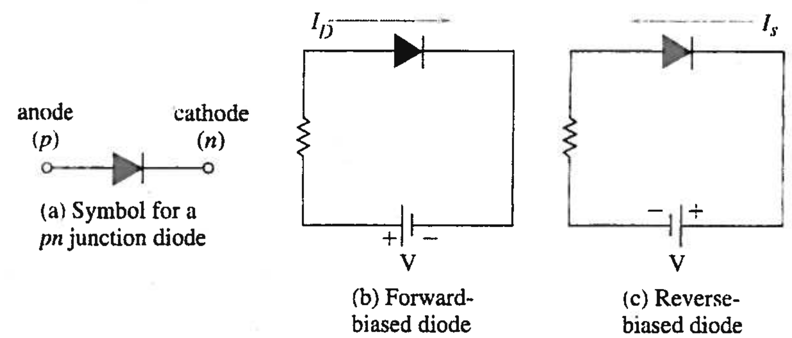


FIGURE 2–11 Diode symbols and bias circuits



current flow when it is forward biased—that makes it a very useful device in many circuit applications. Figure 2–11(a) shows the diode connected to an external source for forward biasing, and 2–11(b) shows reverse biasing. Diode circuits will be studied in detail in Chapter 3.

Returning to our discussion of the reverse-biased junction, we should mention that it is conventional to regard reverse voltage and reverse current as *negative* quantities. When this convention is observed, equation 2–3 can be used to compute reverse current due to a reverse-biasing voltage:

$$I_D = I_s(e^{V_D/\eta V_T} - 1) \tag{2-3}$$

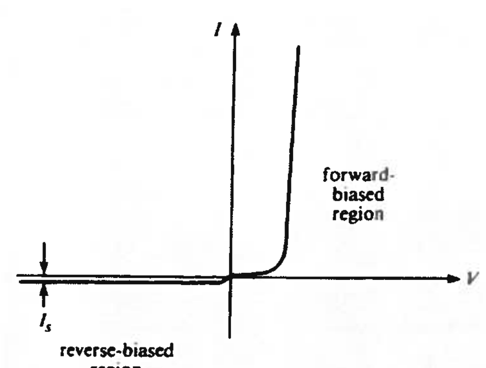
To illustrate, suppose $\eta V_T = 0.05$, $I_s = 0.01$ pA, and the reverse-biasing voltage is $V_D = -0.1$ V. Then

$$I_D = 10^{-14}(e^{-0.1/0.05} - 1) = -0.8647 \times 10^{-14}\text{ A}$$

From the standpoint of plotting the *I*-versus-*V* relationship in a *pn* junction, the sign convention makes further good sense. If forward current is treated as positive (upward), then reverse current should appear below the horizontal axis, i.e., downward, or negative. Similarly, forward voltage is plotted to the right of 0 and reverse voltage is plotted to the left of 0, i.e., in a negative direction. Figure 2–12 shows a plot of I_D versus V_D in which this convention is observed. Note that the current scale is exaggerated in the negative direction, because the magnitude of the reverse current is so very much smaller than that of the forward current.

When V_D is a few tenths of a volt negative in equation 2–3, the magnitude of the term $e^{V_D/\eta V_T}$ is negligible compared to 1. For example, if $V_D = -0.5$, then $e^{V_D/\eta V_T} \approx 4.5 \times 10^{-5}$. Of course, as V_D is made even more negative, the value of $e^{V_D/\eta V_T}$ becomes even smaller. As a consequence, when the junction is reverse biased beyond a few tenths of a volt,

FIGURE 2–12
Current–voltage relations in a *pn* junction under forward and reverse bias. The negative current scale in the reverse-biased region is exaggerated.



$$I_D \approx I_s(0 - 1) = -I_s \tag{2-4}$$

Equation 2–4 shows that the magnitude of the reverse current in the junction under these conditions is essentially equal to I_s, the saturation current. This result accounts for the name *saturation* current: The reverse current predicted by the equation never exceeds the magnitude of I_s.

Equation 2–3 is called the *ideal* diode equation. In real diodes, the reverse current can, in fact, exceed the magnitude of I_s. One reason for this deviation from theory is the existence of *leakage current*, current that flows along the surface of the diode and that obeys an Ohm's law relationship not accounted for in equation 2–3. In a typical silicon diode having $I_s = 10^{-14}$ A, the leakage current may be as great as 10^{-9} A, or 100,000 times the theoretical saturation value.

Breakdown

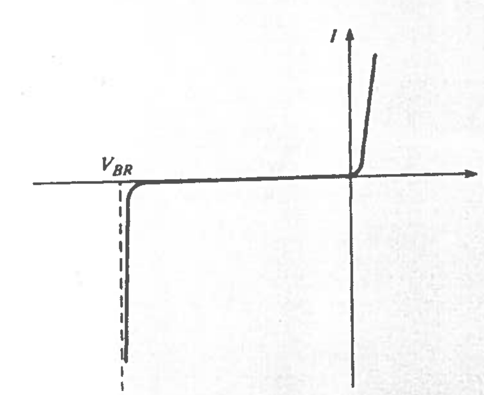
The reverse current also deviates from that predicted by the ideal diode equation if the reverse-biasing voltage is allowed to approach a certain value called the reverse *breakdown* voltage, V_{BR}. When the reverse voltage approaches this value, a substantial reverse current flows. Furthermore, a very small increase in the reverse-bias voltage in the vicinity of V_{BR} results in a very large increase in reverse current. In other words, the diode no longer exhibits its normal characteristic of maintaining a very small, essentially constant reverse current with increasing reverse voltage. Figure 2–13 shows how the current–voltage plot is modified to reflect breakdown. Note that the reverse current follows an essentially vertical line as the reverse voltage approaches V_{BR}. This part of the plot conveys the fact that large increases in reverse current result from very small increases in reverse voltage in the vicinity of V_{BR}.

In ordinary diodes, the breakdown phenomenon occurs because the high electric field in the depletion region imparts high kinetic energy (large velocities) to the carriers crossing the region, and when these carriers collide with other atoms they rupture covalent bonds. The large number of carriers that are freed in this way accounts for the increase in reverse current through the junction. The process is called *avalanching*. The magnitude of the reverse current that flows when V approaches V_{BR} can be predicted from the following experimentally determined relation:

$$I_D = \frac{I_s}{1 - \left(\dfrac{V_D}{V_{BR}}\right)^n} \tag{2-5}$$

where n is a constant determined by experiment and has a value between 2 and 6.

FIGURE 2–13 A plot of the *I–V* relation for a diode, showing the sudden increase in reverse current near the reverse breakdown voltage



Certain special kinds of diodes, called *zener* diodes, are designed for use in the breakdown region. The essentially vertical characteristic in the breakdown region means that the voltage across the diode remains constant in that region, independent of the (reverse) current that flows through it. This property is useful in many applications where the zener diode serves as a *voltage reference*, similar to an ideal voltage source. Zener diodes are more heavily doped than ordinary diodes, and they have narrower depletion regions and smaller breakdown voltages. The breakdown mechanism in zener diodes having breakdown voltages less than about 5 V differs from the avalanching process described earlier. In these cases, the very high electric field intensity across the narrow depletion region directly forces carriers out of their bonds, i.e., strips them loose. Breakdown occurs by avalanching in zener diodes having breakdown voltages greater than about 8 V, and it occurs by a combination of the two mechanisms when the breakdown voltage is between 5 V and 8 V. The characteristics and special properties of zener diodes are discussed in detail in Chapter 3.

Despite the name *breakdown*, nothing about the phenomenon is *inherently* damaging to a diode. On the other hand, a diode, like any other electronic device, is susceptible to damage caused by overheating. Unless there is sufficient current-limiting resistance connected in series with a diode, the large reverse current that would result if the reverse voltage were allowed to approach breakdown could cause excessive heating. Remember that the power dissipation of any device is

$$P = VI \text{ watts} \tag{2-6}$$

where V is the voltage across the device and I is the current through it. At the onset of breakdown, both V (a value near V_{BR}) and I (the reverse current) are likely to be large, so the power computed by equation 2–6 may well exceed the device's ability to dissipate heat. The value of the breakdown voltage depends on doping and other physical characteristics that are controlled in manufacturing. Depending on these factors, ordinary diodes may have breakdown voltages ranging from 10 or 20 V to hundreds of volts.

Temperature Effects

The ideal diode equation shows that both forward- and reverse-current magnitudes depend on temperature, through the thermal voltage term V_T (see equation 2–2). It is also true that the saturation current, I_s in equation 2–2, depends on temperature. In fact, the value of I_s is more sensitive to temperature variations than is V_T, so it can have a pronounced effect on the temperature dependence of diode current. A commonly used rule of thumb is that I_s doubles for every 10°C rise in temperature. The following example illustrates the effect of a rather wide temperature variation on the current in a typical diode.

EXAMPLE 2–6

A silicon diode has a saturation current of 0.1 pA at 20°C. Find its current when it is forward biased by 0.55 V. Find the current in the same diode when the temperature rises to 100°C.

Solution

At $T = 20°C$,

$$V_T = \frac{kT}{q} = \frac{1.38 \times 10^{-23}(273 + 20)}{1.6 \times 10^{-19}} = 0.02527 \text{ V}$$

From equation 2–3, assuming that $\eta = 1$,

$$I = I_s(e^{V_D/\eta V_T} - 1) = 10^{-13}(e^{0.55/0.02527} - 1) = 0.283 \text{ mA}$$

At $T = 100°C$,

$$V_T = \frac{1.38 \times 10^{-23}(273 + 100)}{1.6 \times 10^{-19}} = 0.03217 \text{ V}$$

In going from 20°C to 100°C, the temperature increases in 8 increments of 10°C each: $100 - 20 = 80$; $80/10 = 8$. Therefore, I_s doubles 8 times, i.e., increases by a factor of $2^8 = 256$. So, at 100°C, $I_s = 256 \times 10^{-13}$ A.

$$I = 256 \times 10^{-13}(e^{0.55/0.03217} - 1) = 0.681 \text{ mA}$$

In this example, we see that the forward current increases by a factor of 2.4 or 140% over the temperature range from 20°C to 100°C.

Example 2–6 illustrates that forward current in a diode increases with temperature when the forward voltage is held constant. This result is evident when the *I–V* characteristic of a diode is plotted at two different temperatures, as shown in Figure 2–14. At voltage V_1 in the figure, the current can be seen to increase from I_1 to I_2 as the temperature changes from 20°C to 100°C. (Follow the vertical line drawn upward from V_1—the line of constant voltage V_1.) Note that the effect of increasing temperature is to shift the *I–V* plot toward the left. Note also that when the *current* is held constant, the voltage *decreases* with increasing temperature. At the constant current I_2 in the figure, the voltage can be seen to decrease from V_2 to V_1 as temperature increases from 20°C to 100°C. (Follow the horizontal line drawn through I_2—the line of constant current I_2.) As a rule of thumb, the forward voltage decreases 2.5 mV for each 1°C rise in temperature when the current is held constant.

Of course, temperature also affects the value of reverse current in a diode, because the ideal diode equation (and its temperature-sensitive factors) applies to the reverse- as well as forward-biased condition. In many practical applications, the increase in reverse current due to increasing temperature is a more severe limitation on the usefulness of a diode than is the increase in forward current. This is particularly the case for germanium diodes, which have values of I_s that are typically much larger than those of silicon. In a germanium diode, the value of I_s may be as great as or greater than the reverse leakage current across the surface. Because I_s doubles for every 10°C rise in temperature, the total reverse current through a germanium junction can become quite large with a relatively small increase in temperature. For this reason, germanium devices are not so widely used as their silicon counterparts. Also, germanium devices can withstand temperatures up to only about 100°C, while silicon devices can be used up to 200°C.

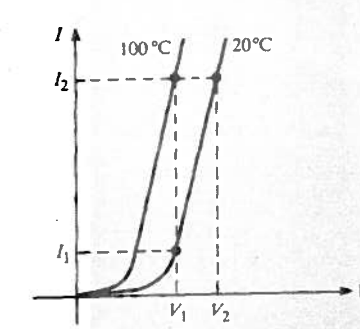


FIGURE 2–14 Increasing temperature causes the forward *I–V* characteristic to shift left

EXAMPLE 2-7

Use SPICE to obtain a plot of the diode current versus diode voltage for a forward-biasing voltage that ranges from 0.0 V to 0.7 V in 5-mV steps. The diode has a saturation current (IS) of 0.01 pA and an emission coefficient (N) of 1.0.

Solution

Figure 2–15(a) shows a diode circuit that can be used by SPICE to perform a .DC analysis of the circuit and the text listing the contents of the .CIR file used to describe the circuit. Although the .MODEL statement specifies the saturation current (IS) and emission coefficient (N), the values used are the same as the default values, so these values could have been omitted. Figure 2–15(b) shows the resulting plot. Note that the current varies from 0 mA to over 5.6 mA. Also note the dramatic increase in the diode current once the diode voltage drop exceeds 0.6 V.

```
* Forward Biased Diode Current
****************************************
* DEFINE THE CIRCUIT ELEMENTS AND NODES
****************************************
V1 1 0 DC 6.0V
R1 1 2 100
D1 2 0 DIODE
*******************************************
* DEFINE THE MODEL PARAMETERS FOR THE DIODE
*******************************************
.MODEL DIODE D IS = 1E-14 N = 1
*************************************************
* PERFORM A DC ANALYSIS ON THE CIRCUIT BY VARYING
* THE VOLTAGE OF V1 FROM ZERO VOLTS TO 0.7 VOLTS
* IN .005 VOLT INCREMENTS
*************************************************
.DC V1 0 1.5 .005
.PROBE
.END
```

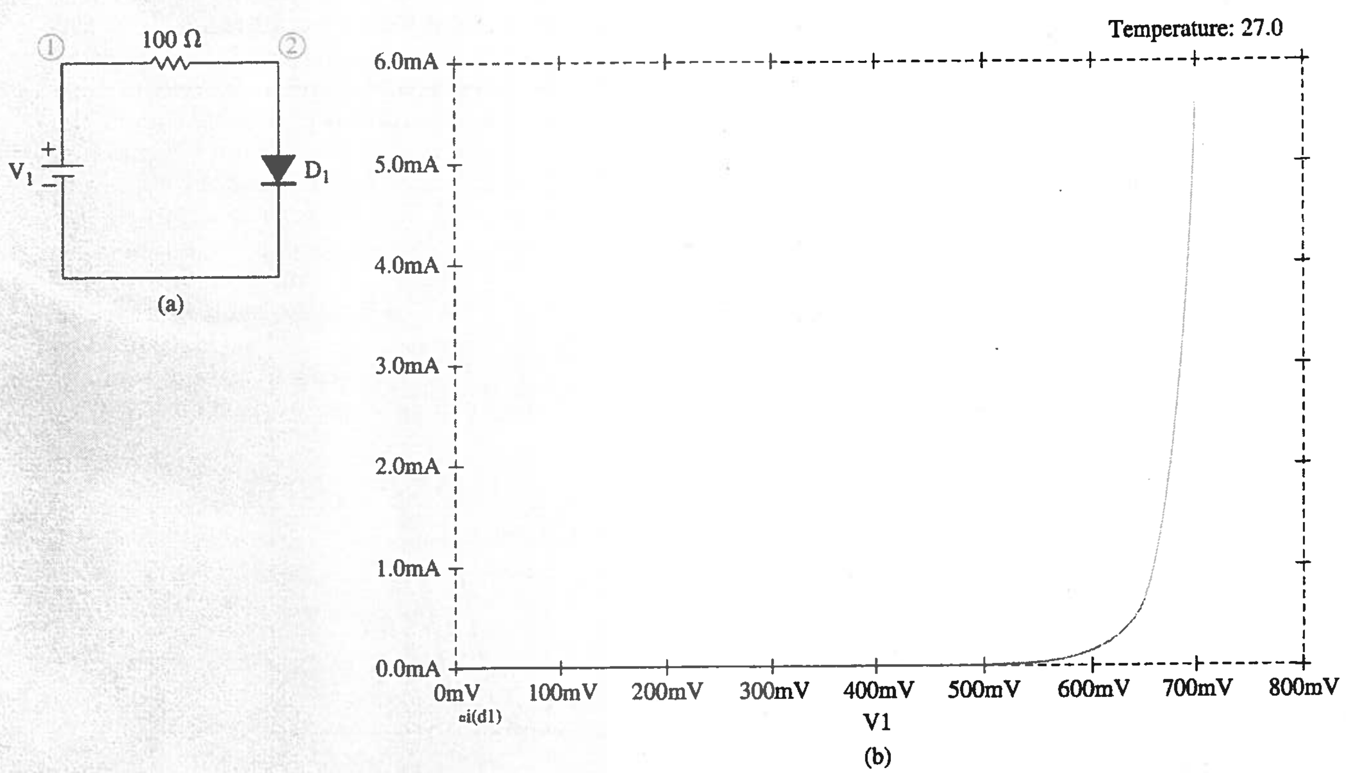


FIGURE 2–15 (a) The circuit for the PSpice simulation used in Example 2–7, (b) SPICE simulation

2-5 IDENTIFYING FORWARD- AND REVERSE-BIAS OPERATING MODES

In an important large-signal application of diodes, the devices are switched rapidly back and forth between their high-resistance and low-resistance states. In these applications, the circuit voltages are pulse-type waveforms, or square waves, that alternate between a "low" voltage, often 0 V, and a "high" voltage, such as +5 V. These essentially instantaneous changes in voltage between low and high cause the diode to switch between its "off" and "on" states. Figure 2–16 shows the voltage waveform that is developed across a resistor in series with a silicon diode when a square wave that alternates between 0 V and +5 V is applied to the combination. When $e(t) = +5$ V, the diode is forward biased, or ON, so current flows through the resistor and a voltage equal to $5 - 0.7 = 4.3$ V is developed across it. When $e(t) = 0$ V, the diode is in its high-resistance state, or OFF, and, because no current flows, the resistor voltage is zero. This operation is very much like rectifier action. However, we study digital logic circuits in just the extreme cases where the voltage is either low or high. In other words, we assume that every voltage in the circuit is at one of those two levels. Because the diode in effect performs the function of switching a high level into or out of a circuit, these applications are often called *switching circuits.*

Diode switching circuits typically contain two or more diodes, each of which is connected to an independent voltage source. Understanding the operation of a diode switching circuit depends first on determining which diodes, if any, are forward biased and which, if any, are reverse biased. The key to this determination is remembering that a diode is forward biased only if its anode is positive *with respect to* its cathode. The important words here (the ones that usually give students the most trouble) are "with respect to." Stated another way, the anode voltage (with respect to ground) must be more positive than the cathode voltage (with respect to ground) in order for a diode to be forward biased. This is, of course, the same as saying that the cathode voltage must be more negative than the anode voltage. Conversely, in order for a diode to be reverse biased, the anode must be negative with respect to the cathode, or, equivalently, the cathode positive with respect to the anode. The following example should help clarify these ideas.

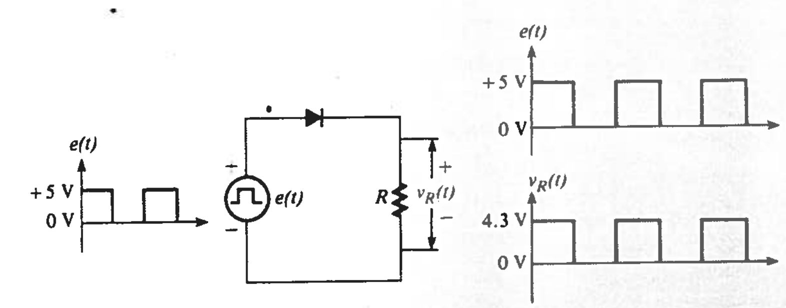


FIGURE 2–16 The diode is forward biased when the square-wave voltage is +5 V. Note that the (silicon) diode voltage is 0.7 V when it conducts.

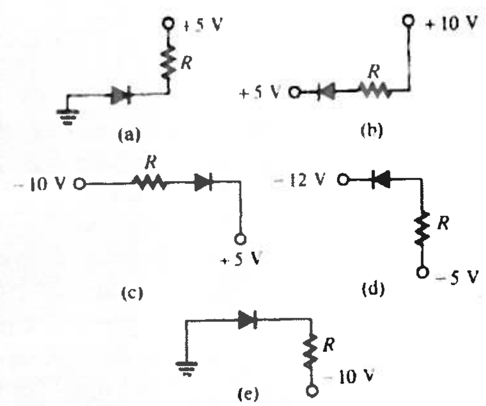


FIGURE 2–17 Forward- and reverse-biased diode configurations

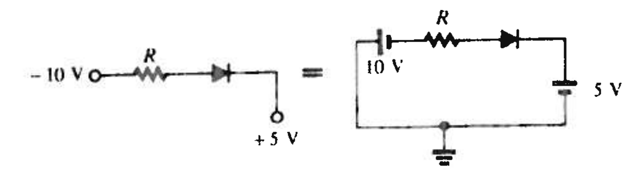


FIGURE 2–18 The circuit of Figure 2–17(c) is redrawn in an equivalent form that shows all ground connections

EXAMPLE 2–8

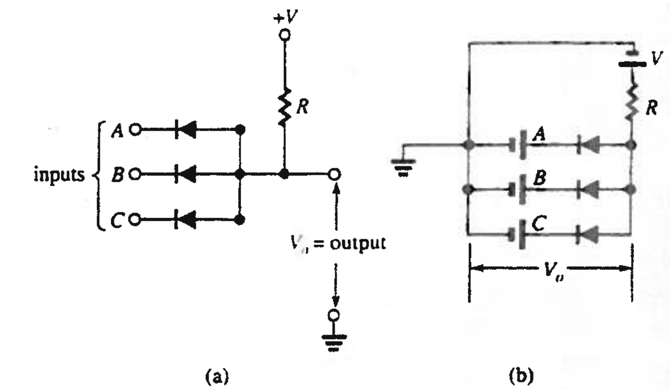
Determine which diodes are forward biased and which are reverse biased in each of the configurations shown in Figure 2–17. The schematic diagrams in each part of Figure 2–17 are drawn using the standard convention of omitting the connection line between one side of a voltage source and ground. In this convention, it is understood that the *opposite* side of each voltage source shown in the figure is connected to ground. If the reader is not comfortable with this convention, then he or she should begin the process now of becoming accustomed to it, for it is widely used in electronics. As an aid in understanding the explanations given below, redraw each circuit with all ground connections included. For example, Figure 2–18 shows the circuit that is equivalent to Figure 2–17(c).

Solution

1. In (a) the anode is grounded and is therefore at 0 V. The cathode side is positive by virtue of the +5-V source connected to it through resistor R. The cathode is therefore positive with respect to the anode; i.e., the anode is more negative than the cathode, so the diode is reverse biased.
2. In (b) the anode side is more positive than the cathode side ($+10\,\text{V} > +5\,\text{V}$), so the diode is forward biased. Current flows from the 10-V source, through the diode, and into the 5-V source.
3. In (c) the anode side is more negative than the cathode side, so the diode is reverse biased. Note that (essentially) no current flows in the circuit, so there is no drop across resistor R. Therefore, the total reverse-biasing voltage across the diode is 15 V. (See also Figure 2–18, and note that the sources are series-adding.)
4. In (d) the cathode side is more negative than the anode side ($-12\,\text{V} < -5\,\text{V}$), so the diode is forward biased. Current flows from the −5-V source, through the diode, and into the −12-V source.
5. In (e) the anode is grounded and is therefore at 0 V. The cathode side is more negative than the anode side ($-10\,\text{V} < 0\,\text{V}$), so the diode is forward biased. Current flows from ground, through the diode, and into the − 10-V source.

Figure 2–19 shows a diode switching circuit. It consists of three diodes whose anodes are connected together and whose cathodes may be connected to independent voltage sources. The voltage levels connected to the cathodes are called *inputs* to the circuit, labeled *A*, *B*, and *C*, and the voltage developed at the point where the anodes are joined is called the *output* of the circuit. All voltages are referenced to the circuit's common ground. The voltage source V is a fixed positive voltage called the *supply* voltage. The figure shows the conventional way of drawing this kind of circuit (a), and the complete equivalent circuit (b).

FIGURE 2–19 A typical diode switching circuit like those used in digital logic applications. The equivalent circuit, showing all ground paths, is shown in (b)



Let us assume that the inputs A, B, and C in Figure 2–19 can be either +5 V (high) or 0 V (low). Suppose further that the supply voltage is $V = +10$ V. If A, B, and C are all +5 V, then all three diodes are forward biased ($+10 > +5$) and are therefore conducting. Current flows from the 10-V source, through the resistor, and then divides through the three diodes. See Figure 2–20.

Typically, the dc resistance of the diode is not known and an approximate solution can be obtained by assuming a 0.7-V drop across each (silicon) diode. Under this assumption, the equivalent circuit appears as shown in Figure 2–21. Using this equivalent circuit, we can clearly see that $V_o = 5\,\text{V} + 0.7\,\text{V} = 5.7\,\text{V}$.

Suppose now that input $A = 0$ V and $B = C = +5$ V, as shown in Figure 2–22(a). It is clear that the diode connected to input A is forward biased. If we temporarily regard the "ON" diode as a perfect closed switch, then we see that the anode side of all diodes will be connected through this closed switch to 0 V. Therefore, the other two diodes have +5 V on their cathodes and 0 V on their anodes, causing them to be reverse biased. In reality, the "ON" diode is not a perfect switch, so it has some small voltage drop across it and the

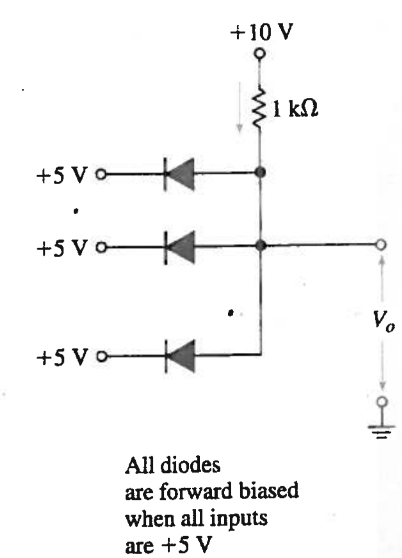


FIGURE 2–20 The diode circuit of Figure 2–19 when all inputs are +5 V

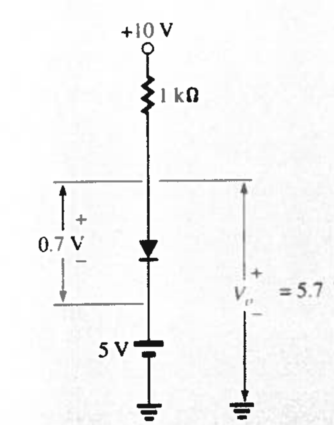
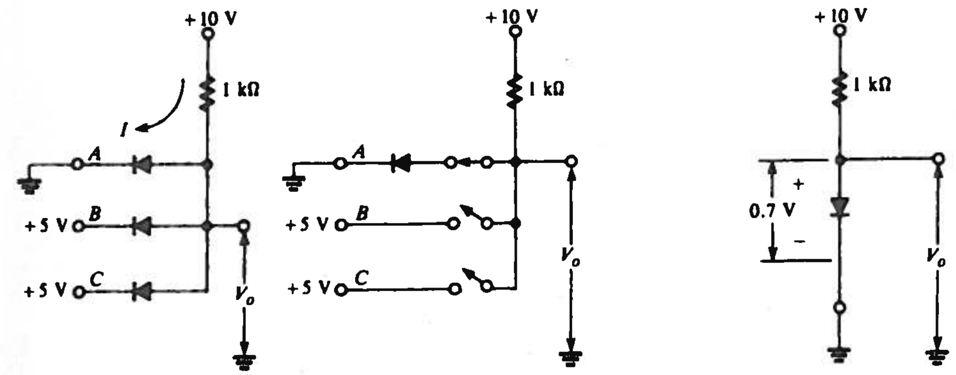


FIGURE 2–21 The circuit that is equivalent to Figure 2–20(a) when the diodes are assumed to have a fixed 0.7-V drop



(a) Diode *A* is forward biased.

(b) Diodes *B* and *C* are reverse biased and replaced by equivalent open switches.

(c) The circuit equivalent to (a) when the diode is assumed to have a 0.7-V drop.

FIGURE 2–22 The circuit of Figure 2–19 when input *A* is 0 V and inputs *B* and *C* are +5 V

anodes are *near* 0 V rather than exactly 0 V. The net effect is the same: One diode is forward biased and the other two are reverse biased.

Figure 2-22(b) shows the equivalent circuit that results if we treat the reverse-biased diodes as open switches. Figure 2–22(c) shows the equivalent circuit that results when we assume that the diode voltage drop is 0.7 V. In this case, we see that $V_o = 0.7$ V.

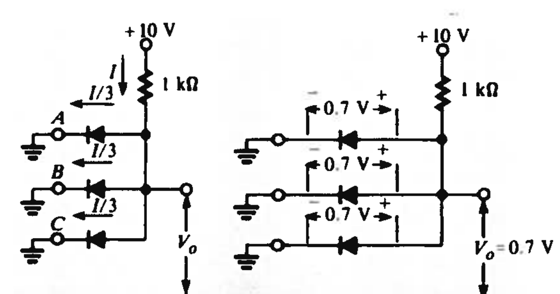
If input *B* is at 0 V while $A = C = +5$ V, then it should be obvious that the output voltage V_o is exactly the same as in the previous case. Any combination of inputs that causes one diode to be forward biased and the other two to be reverse biased has the same equivalent circuits as shown in Figure 2–22.

When any two of the inputs are at 0 V and the third is at +5 V, then two diodes are forward biased and the third is reverse biased. It is left as an exercise to determine the output voltage in this case.

Finally, if all three inputs are at 0 V, then all three diodes are forward biased. The equivalent circuits are shown in Figure 2–23. If we regard the drop across each diode as 0.7 V, then $V_o = 0.7$ V, as shown in Figure 2–23(b). The diode circuit we have just analyzed is called a diode AND gate because the output is high if and only if inputs *A and B and C* are all high.

We have seen that the first step in this kind of analysis is to determine which diodes are forward biased and which are reverse biased. This determination is best accomplished by temporarily regarding each diode as a perfect, voltage-controlled switch. At this point, one might legitimately question how

FIGURE 2–23 The circuit of Figure 2–19 when all inputs are 0 V



(a) All diodes are forward biased.

(b) The circuit equivalent to (a) when all diodes are assumed to have a 0.7-V drop.

we determined that the forward-biased diode shown in Figure 2–22 is the only one that is forward biased. After all, the other two diodes appear to have their anode sides more positive (10 V) than their cathode sides (5 V) and seem therefore to meet the criterion for forward bias. However, if D_1 is forward biased, its anode voltage will be +0.7 V forcing the other two diodes to be reverse biased, because their cathodes are more positive than their anodes.

A rule that is useful for determining which diode is truly forward biased is to determine which one has the greatest forward-biasing potential measured from the supply voltage to its input voltage. For example, in Figure 2–22, the net voltage between the supply and input *A* is 10 V − 0 V = 10 V, while the net voltage between the supply and inputs *B* and *C* is +10 V − 5 V = 5 V. Therefore, the first diode is forward biased and the other two diodes are reverse biased.

EXAMPLE 2–9

Determine which diodes are forward biased and which are reverse biased in the circuits shown in Figure 2–24. Assuming a 0.7-V drop across each forward-biased diode, determine the output voltage.

Solution

1. In (a) diodes D_1 and D_3 have a net forward-biasing voltage between supply and input of 5 V − 5 V = 0 V. Diodes D_2 and D_4 have a net forward-biasing voltage of 5 V − (−5 V) = 10 V. Therefore, D_2 and D_4 are forward biased and D_1 and D_3 are reverse biased. Figure 2–25 shows the equivalent circuit path between input and output. Writing Kirchhoff's voltage law around the loop, we determine $V_o = -5\text{ V} + 0.7\text{ V} = -4.3$ V.
2. In (b) the net forward-biasing voltage between supply and input for each diode is

D_1: +15 V − (+5 V) = +10 V

D_2: +15 V − 0 V = +15 V

FIGURE 2–24 (Example 2–9)

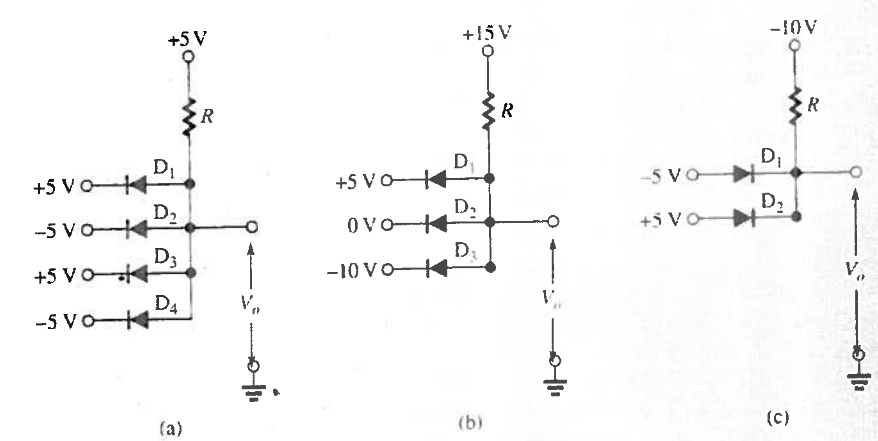


FIGURE 2–25 The circuit equivalent to Figure 2–24(a)

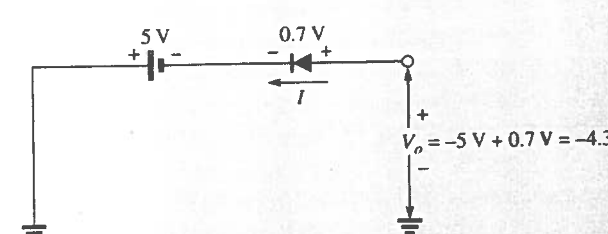
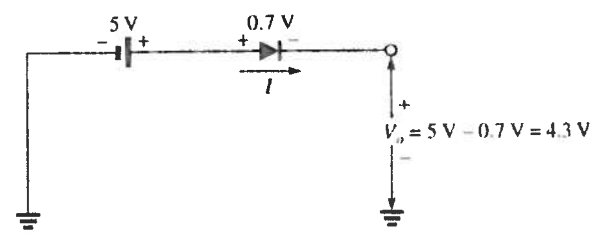


FIGURE 2–26 The circuit equivalent to Figure 2–24(c)



D_3: +15 V − (−10 V) = +25 V

Therefore, D_3 is forward biased and D_1 and D_2 are reverse biased.

$V_o = -10\text{ V} + 0.7\text{ V} = -9.3\text{ V}$

3. In (c) the net forward-biasing voltage between supply and input for each diode is

D_1: −10 V − (−5 V) = −5 V

D_2: −10 V − (+5 V) = −15 V

Notice that the diode positions are reversed with respect to those in (a) and (b), in the sense that the cathodes are joined together and connected through resistor R to a negative supply. Thus, the diode for which there is the greatest negative voltage between supply and input is the forward-biased diode. In this case, that diode is D_2. D_1 is reverse biased, by virtue of the fact that its cathode is near +5 V and its anode is at −5 V. Figure 2–26 shows the equivalent circuit path between input and output. Writing Kirchhoff's voltage law around the loop, we see that $V_o = 5\text{ V} - 0.7\text{ V} = 4.3\text{ V}$.

2–6 *pn* JUNCTION CAPACITANCE

In a *pn* junction, a small parasitic capacitance exists due to the charges associated with the ionized donor and acceptor atoms. This capacitance exists both in the reverse- and forward-bias modes. The capacitance is extremely important when studying *pn* junctions because it affects frequency behavior. For many high-frequency circuits, parasitics will limit the overall performance. The parasitic capacitance can also have beneficial behavior. For a reverse-biased diode, the width of the depletion region increases as the reverse-biasing voltage increases. Thus, increasing the reverse-bias voltage on a diode causes the distance (d) to increase in the capacitive plates. Recall that a capacitor is constructed by two plates separated by a dielectric. In this case, the plates are formed by the *p* and *n* regions, and the dielectric is provided by the depletion region. The capacitance equation is

$$C = \frac{\varepsilon A}{d} \qquad (2\text{–}7)$$

where ε is the permittivity of the dielectric, A is the cross-sectional surface area of the conducting region, and d is the distance separating the regions (the thickness, or width, of the dielectric). Thus, increasing the reverse bias on a diode causes d to increase and the capacitance $C = \varepsilon A/d$ to decrease. This behavior is the fundamental principle governing the operation of a *varactor diode.* The capacitance value obtained from a varactor diode is small, on the order of 100 pF or less and is used in practice only to alter the ac impedance it presents to a high-frequency signal. For example, it can be used in tuned LC networks (also called "tank" circuits). The equation for calculating the junction capacitance (C_j) is

$$C_j = \frac{C_{jo}}{\sqrt{1 + \dfrac{V_R}{\psi_o}}} \qquad (2\text{–}8)$$

where C_{jo} = zero-bias capacitance
V_R = *pn* junction reverse-voltage bias (magnitude)
ψ_o = zero-bias voltage potential

EXAMPLE 2–10

Given that the zero-bias capacitance of a *pn* junction is 2 pF and the zero-bias voltage potential is 0.55 V, calculate the capacitance of the *pn* junction if the reverse-bias voltage bias is 9.0 V.

Solution

$C_{jo} = 2\text{ pF}$

$V_R = 9.0\text{ V}$

$\psi_o = 0.55\text{ V}$

$$C_j = \frac{2.0}{\sqrt{1 + \dfrac{9.0}{.55}}} = 0.479\text{ pF}$$

An important characteristic of a varactor diode is the ratio of its largest to its smallest capacitance when the voltage across it is adjusted through a specified range. Sometimes called the capacitance *tuning ratio*, this value is governed by the *doping profile* of the semiconductor material used to form the *p* and *n* regions, that is, the doping density in the vicinity of the junction. In diodes having an *abrupt* junction, the *p* and *n* sides are uniformly doped, and there is an abrupt transition from *p* to *n* at the junction. Abrupt-junction varactors exhibit capacitance ratios from about 2:1 to 3:1. In the *hyperabrupt* (extremely abrupt) junction, the doping level is increased as the junction is approached from either side, so the *p* material becomes more heavily *p* near the junction, and the *n* material becomes more heavily *n*. The hyperabrupt junction is very sensitive to changes in reverse voltage, and this type of varactor may have a capacitance ratio up to 20:1. Figure 2–27 shows typical plots of abrupt and hyperabrupt varactor capacitance versus reverse voltage. The figure also shows the schematic symbol for a varactor diode.

2–7 CIRCUIT ANALYSIS WITH ELECTRONICS WORKBENCH MULTISIM

This text present simulation examples of circuit analysis of fundamental electronic circuits using Electronics Workbench Multisim (EWB). Examples of key analog circuit concepts are presented in each chapter. EWB provides a unique opportunity for the student to examine electronic circuits and analog concepts in a way that reflects techniques used on both the bench and on the computer. The use of EWB provides the student with additional hands-on insight into many of the fundamental analog circuits, concepts, and test equipment while improving the student's ability to perform logical thinking when troubleshooting circuits and systems. The test equipment tools in EWB reflect the type of tools that are common on well-equipped test benches, and the analysis tools reflect the type of analytical tools available.

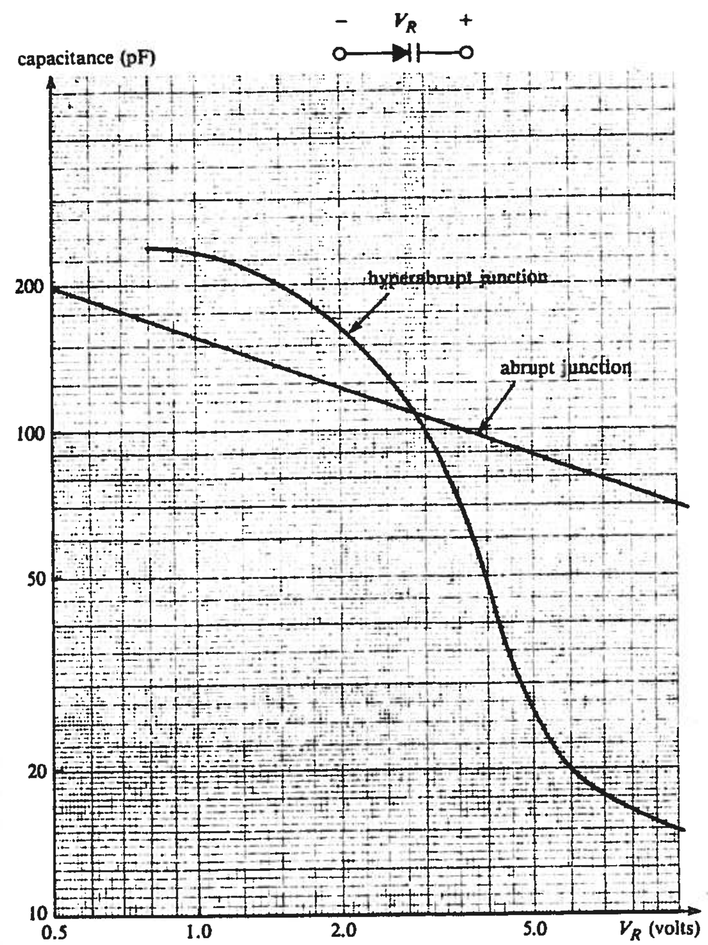


FIGURE 2–27 Capacitance versus reverse voltage for abrupt and hyperabrupt varactor diodes

Chapter 2 introduced the basic concept of the *pn* junction (a diode). The student learned that the voltage drop across a forward-biased ideal diode is 0.7 V. The following exercise demonstrates how a computer simulation package such as EWB can be used to test and analyze a basic diode circuit. The objectives of this exercise are as follows:

- Show the student how to construct and simulate a simple diode circuit.
- Use EWB to show that the forward voltage drop across an ideal diode is 0.7 V.
- Use EWB to measure the current flowing in the circuit.

Open the circuit, **Ch2_EWB.msm** that is found in the Electronics Workbench 2001 CD-ROM packaged with the text. This is a simple circuit (shown in Figure 2-28) containing a +12 V voltage source, a 1-kΩ resistor and an ideal diode. Two multimeters are being used in this circuit: One is being used to measure the diode voltage drop, and the other is used to measure the current in the circuit. The voltage measurement requires that the multimeter be set to DC and V selected. The current meter is set to measure DC current (A). Notice that the current meter is in series with the diode and the power supply.

Each multimeter has a settings button. This is shown in Figure 2–29. The user of the multimeter has the capability to adjust the settings for ammeter resistance, volmeter resistance, and ohmmeter current. Remember, real test gear has some resistance or requires some current to make a measurement. These settings simulate "real-world" conditions.

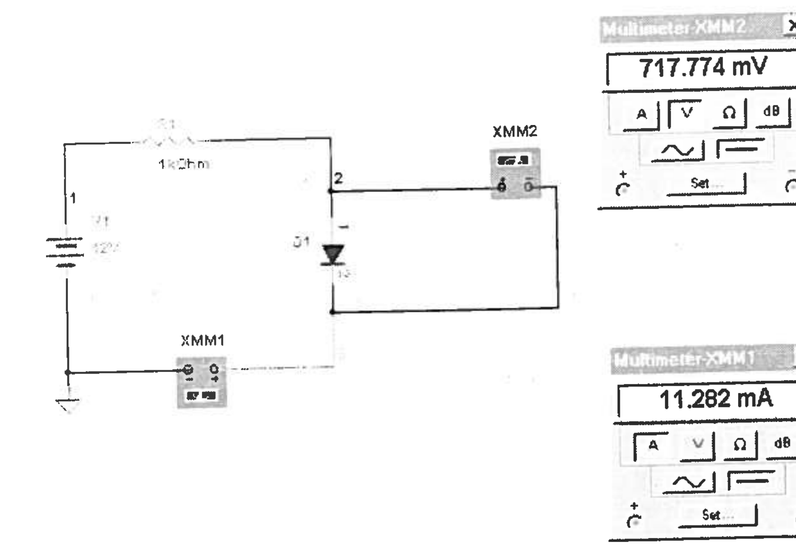


FIGURE 2–28 The simple diode circuit for the EWB exercise

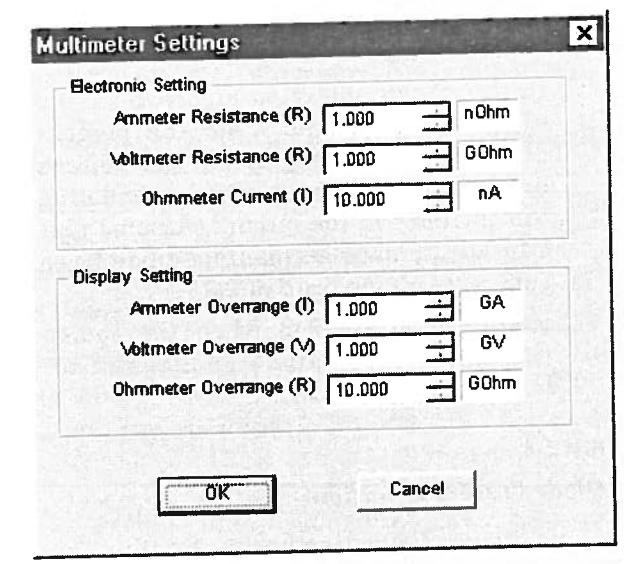


FIGURE 2–29 The setting options for the EWB multimeters

A key to success with computer simulation of electronic circuits is to have a reasonable ballpark estimate of what the expected voltages and currents should be. The expected voltage drop should be about 0.7 V and the current should be about (12 − 0.7)/1k = 11.3 mA. The computer simulation is started by clicking on the simulation start button. The multimeters will immediately display results. The voltmeter shows a value of 771.774 mV. The current meter shows 11.282 mA.

SUMMARY

This chapter has presented the basics of the *pn* junction. Students should have mastered the following concepts and skills:

- Identifying forward and reverse biased diodes.
- Understanding that current flows in a forward-bias diode and essentially no current flows in a reverse-bias diode.

- Knowing that the voltage drop across an ideal forward-biased diode is approximately 0.7 V.
- Analyzing a basic diode circuit to determine currents and voltages.

EXERCISES

SECTION 2-3
Basic Diode Operation

2-1. Assume that the voltage drop across a forward-biased silicon diode is 0.7 V and that across a forward-biased germanium diode is 0.3 V.
  (a) If D_1 and D_2 are both silicon diodes in Figure 2-30, find the current I in the circuit.
  (b) Repeat if D_1 is silicon and D_2 is germanium.

2-2. Repeat Exercise 2-1 when the constant source voltage is changed to 9 V.

2-3. In the circuit shown in Figure 2-31, the diode is germanium: Find the percent error caused by neglecting the voltage drop across the diode when calculating the current I in the circuit. (Assume that a forward-biased germanium diode has a constant voltage drop of 0.3 V.)

2-4. Repeat Exercise 2-3 when the source voltage is changed to 3 V and the resistor is changed to 470 Ω.

SECTION 2-4
The Diode Current Equation

2-5. A silicon *pn* junction has a saturation current of 1.8×10^{-14} A. Assuming that $\eta = 1$,

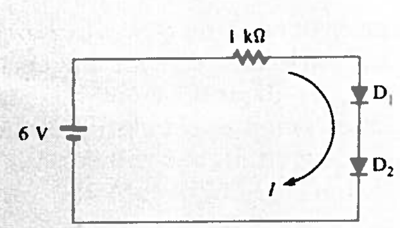


FIGURE 2-30 (Exercise 2-1)

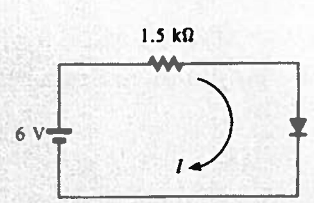


FIGURE 2-31 (Exercise 2-3)

find the current in the junction when the forward-biasing voltage is 0.6 V and the temperature is 27°C.

2-6. Repeat Exercise 2-5 when the forward-biasing voltage is 0.65 V.

2-7. The forward current in a *pn* junction is 1.5 mA at 27°C. If $I_s = 2.4 \times 10^{-14}$ A and $\eta = 1$, what is the forward-biasing voltage across the junction?

2-8. The forward current in a *pn* junction is 22 mA when the forward-biasing voltage is 0.64 V. If the thermal voltage is 26 mV and $\eta = 1$, what is the saturation current?

2-9. A junction diode has an external voltage source of 0.15 V connected across it, with the positive terminal of the source connected to the cathode of the diode. The saturation current is 0.02 pA, the thermal voltage is 26 mV, and $\eta = 2$.
  (a) Find the theoretical (ideal) diode current. Repeat for a source voltage of
  (b) 0.3 V, and
  (c) again for a source voltage of 0.5 V.

2-10. A junction diode is connected across an external voltage source so that the negative terminal of the source is connected to the anode of the diode. If the external voltage source is 5 V and the saturation current is 0.06 pA, what is the theoretical (ideal) diode current?

2-11. The reverse breakdown voltage of a certain diode is 150 V and its saturation current is 0.1 pA. Assuming that the constant n in equation 2-5 is 2, what is the current in the diode when the reverse-biasing voltage is 149.95 V?

2-12. In an experiment designed to investigate the breakdown characteristics of a certain diode, a reverse current of 9.3 nA was measured when the reverse voltage across the diode was 349.99 V. If the breakdown voltage of the diode was 350 V and its saturation current was known to be 1.0 pA, what value of the constant n in equation 2-5 is appropriate for this diode?

2-13. The manufacturer of a certain diode rates its maximum power dissipation as 0.1 W and its reverse breakdown voltage as 200 V. What maximum reverse current could it sustain at breakdown without damage?

2-14. A certain diode has a reverse breakdown voltage of 100 V and a saturation current of 0.05 pA. How much power does it dissipate when the reverse voltage is 99.99 V? Assume that n in equation 2-5 is 2.5.

2-15. A diode has a saturation current of 45 pA at a temperature of 373 K. What is the approximate value of I_s at $T = 273$ K?

2-16. When the voltage across a forward-biased diode at $T = 10$°C is 0.621 V, the current is 4.3 mA. If the current is held constant, what is the voltage when,
  (a) $T = 40$°C?
  (b) Repeat for $T = -30$°C.

SECTION 2-5
Identifying Forward- and Reverse-Bias Operating Modes

2-17. Determine which of the diodes in Figure 2-32 are forward biased and which are reverse biased.

2-18. Determine which of the diodes shown in Figure 2-33 are forward biased and which are reverse biased.

2-19. The inputs A and B in Figure 2-34 can be either 0 V or +10 V. Each diode is silicon. Find V_o for each of the following cases. (Assume ideal silicon diodes.)
  (a) $A = 0$ V, $B = 0$ V
  (b) $A = 0$ V, $B = +10$ V

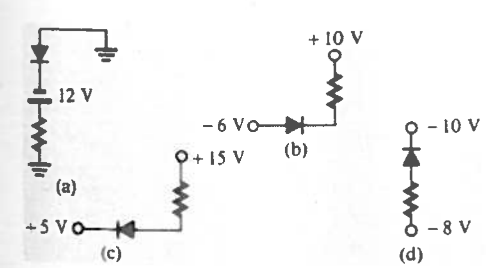


FIGURE 2-32 (Exercise 2-17)

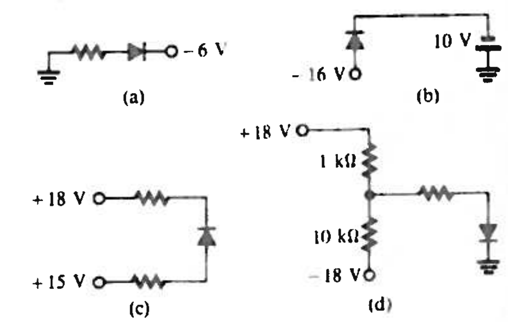


FIGURE 2-33 (Exercise 2-18)

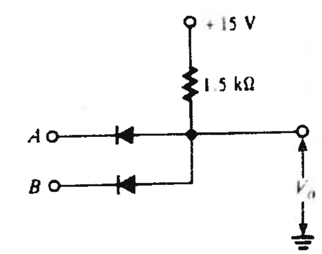


FIGURE 2-34 (Exercise 2-19)

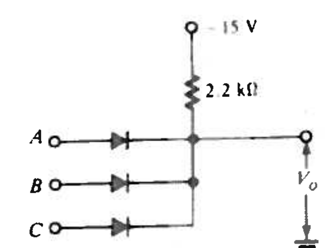


FIGURE 2-35 (Exercise 2-20)

  (c) $A = +10$ V, $B = 0$ V
  (d) $A = +10$ V, $B = +10$ V

2-20. The inputs A, B, and C in Figure 2-35 can be either +10 V or −5 V. Assume ideal silicon diodes. Find V_o when
  (a) $A = B = C = -5$ V
  (b) $A = C = -5$ V, $B = +10$ V
  (c) $A = B = +10$ V, $C = -5$ V
  (d) $A = B = C = +10$ V

2-21. In the circuit of Exercise 2-20, A, B, and C can be either 0 V or −5 V. Assuming that the forward $V_D = 0.7$ V, find V_o when
  (a) $A = B = C = 0$ V
  (b) $A = B = 0$ V, $C = -5$ V
  (c) $A = C = -5$ V, $B = 0$ V
  (d) $A = B = C = -5$ V

2-22. In the circuit of Exercise 2–19, A and B can be either 0 V or −5 V. Assuming that the forward $V_D = 0.7$ V, find V_o when

(a) $A = B = -5$ V

(b) $A = -5$ V, $B = 0$ V

(c) $A = 0$ V, $B = -5$ V

(d) $A = B = 0$ V

SECTION 2–6

***pn* Junction Capacitance**

2-23. Given that the zero-bias capacitance of a *pn* junction is 5 pF and the zero-bias voltage potential is 0.62 V, calculate the capacitance of the *pn* junction if the reverse-bias voltage-bias is 10.0 V.

2-24. Given that a diode, with an abrupt junction, has the capacitance-versus-reverse-voltage curve shown in Figure 2–25, determine the capacitance range as the reverse-bias voltage is varied from 1.0 V to 5.0 V.

2-25. Given that $\varepsilon = 1.04 \times 10^{-12}$ F/cm, the plate area is 2 cm^2, and the width of the dielectric is 1 μ (1×10^{-6} meters), calculate the capacitance.

2-26. Given that the zero-bias capacitance of a *pn* junction is 7 pF and the zero-bias voltage potential is 0.65 V, calculate the capacitance of the *pn* junction if the reverse-bias voltage bias is

(a) 2.5 V,

(b) 5.0 V,

(c) 8.8 V.

SPICE EXERCISES

Note: In the exercises that follow, assume that all device parameters have their default values unless otherwise specified.

2-27. Use SPICE to simulate the circuit shown in Figure 2–4. Obtain a value for the current I.

2-28. Use SPICE to simulate the circuit shown in Figure 2–5. Obtain a value for the current I and the voltage across diode D_1.

2-29. Use SPICE to simulate the circuit shown in Figure 2–6. Obtain a value for the current I and the voltage V_{AB}.

2-30. Use SPICE to simulate the circuit shown in Figure 2–20. Obtain a value for the output voltage V_o.

CHAPTER 3

THE DIODE AS A CIRCUIT ELEMENT

OUTLINE

OBJECTIVES

- Develop an understanding of the operation of diodes in dc circuits.
- Differentiate between the concepts of ac and dc resistance in diodes.
- Understand the load line concept in a simple diode circuit.
- Graphically visualize the half-wave and full-wave rectification process.
- Recognize the effect of capacitive filtering in a rectifier.
- Specify components for a simple power supply.

3–1 INTRODUCTION

In Chapter 2 we studied the construction and properties of a *pn* junction and mentioned that a semiconductor diode is an example of an electronic device that contains such a junction. We learned about the *I–V* relationship (the diode equation) that describes mathematically the behavior of a diode and used it for obtaining the operating voltage and current in a simple diode circuit. We also learned to identify in a circuit when a diode is forward or reverse biased and used this fact in the analysis of diode logic circuits.

In this chapter we will study the diode as a circuit *device* or component of an electronic circuit with a specific function. We will also learn about modeling a diode as an ideal or semi-ideal device by replacing it with a simpler *equivalent* circuit element. This approach will serve as our introduction to this standard and widely used method of electronic circuit analysis: Replace actual devices by simpler equivalent circuits in order to obtain solutions that are sufficiently accurate for the application in which they are used. This *analysis* method allows us to use standard procedures of solution for dc and ac circuits. Understand that this "replacement" of the diode by its equivalent circuit is done on paper only, in order to simplify calculations.

Studying and understanding important concepts such as linearity, small- and large-signal operation, quiescent points, bias, load lines, and equivalent circuits are best accomplished by applying them to the analysis of the relatively simple diode circuit. In later chapters we will apply our knowledge of diode circuit analysis to the study of several practical circuits in which these versatile devices are used.

Finally, this chapter will cover elementary *power supplies* (electronic circuits used for converting ac voltage to dc voltage) where diodes play a very important role. A section on elementary *voltage regulation* is included with the aim of allowing students to build their own multi-voltage power supply early in the course.

3–2 THE DIODE AS A NONLINEAR DEVICE

Linearity is an exceptionally important concept in electronics. For our purposes now, we can best understand the practical implications of this rather broad concept by restricting ourselves to the following definition of a linear

electronic device: *A device is linear if the graph relating the voltage across it to the current through it is a straight line.*

If we have experimental data that shows measured values of voltage and the corresponding values of current, then it is a simple matter to plot these and determine whether the linearity criterion is satisfied. Often we have an equation that relates the voltage across a device to the current through it (or that relates the current to the voltage). If the equation is in one of the general *forms*

$$V = a_1 I + a_2 \tag{3–1}$$

or

$$I = b_1 V + b_2 \tag{3–2}$$

where a_1, a_2, b_1, and b_2 are any constants, positive, negative, or 0, then the graph of V versus I is a straight line and the device is linear. In equation 3–1, a_1 is the *slope* of the line and has the units of ohms. In equation 3–2, b_1 is the slope and has the units siemens (formerly mhos).

In fundamental circuit analysis courses, we learn that resistors, capacitors, and inductors are all linear electrical devices because their voltage–current equations are of the form of equations 3–1 and 3–2, such as $V = IR$, $I = VY$, $V_L = I_L X_L$, or $I_C = V_C/X_C$, to name a few.

In these voltage–current equations, we of course assume that any other circuit characteristics such as frequency are held constant. In other words, only the magnitudes of voltage and current are regarded as variables. In each case, all else being equal, increasing or decreasing the voltage causes a proportional increase or decrease in the current. Figure 3–1 is a plot of the voltage V across a 200-Ω resistor versus the current I through it. The linearity property of the resistor is clearly evident and follows from the Ohm's law relation $V = 200I$. Note that the slope of the line equals the resistance, $r = \Delta V/\Delta I = 200\ \Omega$, and that the linear relation applies to *negative* voltages and currents as well as positive. Reversing the directions (polarities) of the voltage across and current through a linear device does not alter its linearity property. Note also that the slope of the line is everywhere the same: No matter where along the line the computation $\Delta V/\Delta I$ is performed, the result equals 200 Ω.

When displaying the voltage–current relationship of an electronic device on a graph, it is conventional to plot current along the vertical axis and voltage along the horizontal axis—the reverse of that shown in Figure 3–1. Of course, the graph of a linear device is still a straight line; reversal of axes is equivalent to expressing the V–I relation in the form of equation 3–2, with slope having the units of conductance, $G = \Delta I/\Delta V = 1/R$ (siemens) instead of resistance.

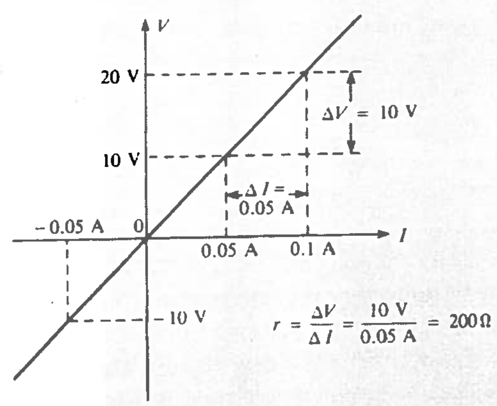


FIGURE 3–1 The graph of V versus I for a resistor is a straight line. A resistor is a linear device, and the value of $\Delta V/\Delta I$ is the same no matter where it is computed.

In Chapter 2 we stated that the current–voltage relation for a *pn* junction (and therefore for a diode) is

$$I_D = I_s(e^{V_D/\eta V_T} - 1) \tag{3-3}$$

where I_s = saturation current
V_T = thermal voltage ≈ 26 mV at room temperature
η = a function of V_D, whose value ranges between 1 and 2

Equation 3–3 is clearly not in the form of either equation 3–1 or 3–2, so the diode's voltage–current relation does not meet the criterion for a linear electronic device. We conclude that a diode is a *nonlinear* device. Figure 3–2 is a graph of the *I–V* characteristic of a typical silicon diode in its forward-biased region. The graph is most certainly not a straight line.

Figure 3–2 shows how identical ΔV values result in different ΔI values along the *I–V* curve, revealing that the resistance $\Delta V/\Delta I$ decreases (steeper slope) as diode current increases. Unlike a linear device, the resistance of a nonlinear device depends on the voltage across it (or current through it)—i.e., the resistance depends on the point where the values of ΔV and ΔI are calculated—specifically, at the biasing or operating point. In the case of a diode, we further note that the *I–V* characteristic becomes very nearly horizontal at low values of current and in the reverse-biased region (see Figure 2–12). Therefore, in these regions, large changes in voltage, ΔV, create very small changes in current, ΔI, so the value of $\Delta V/\Delta I$ is very large.

The region on the *I–V* curve where the transition from high resistance to low resistance takes place is called the *knee* of the curve. When the diode current is significantly greater or less than that in the vicinity of the knee, we will say that it is biased *above* or *below* the knee, respectively. The biasing point is also called the *quiescent* point or *Q*-point, for short.

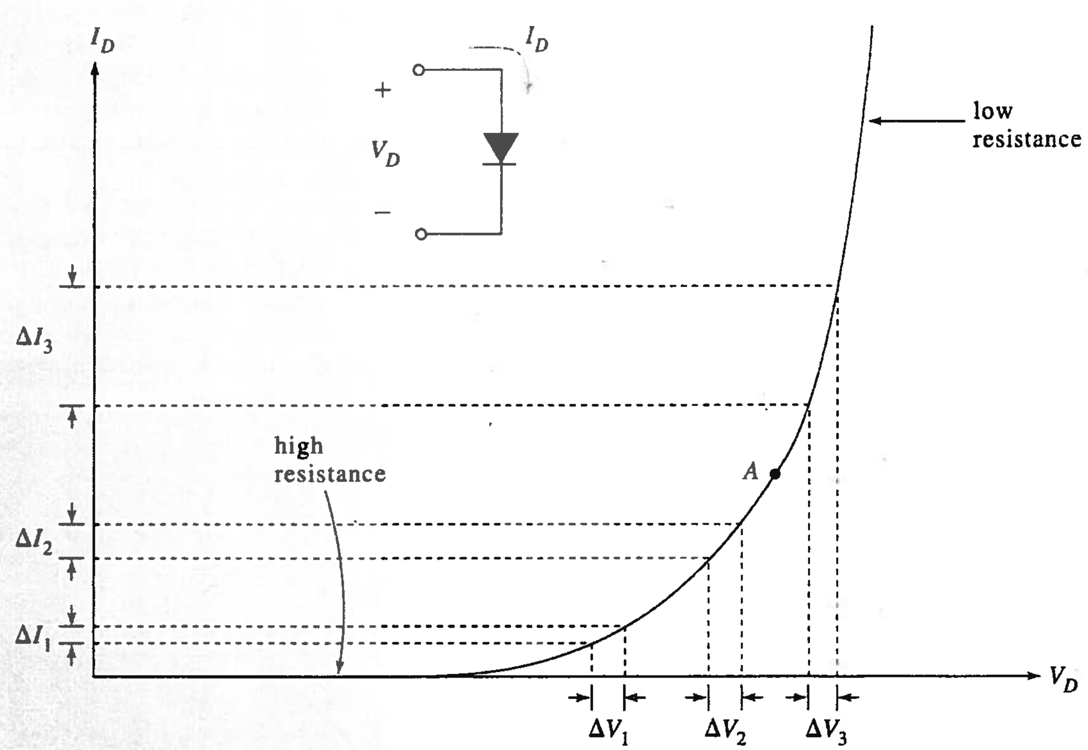


FIGURE 3–2 A forward-biased diode characteristic. The value of $\Delta I/\Delta V$ depends upon the location where it is computed.

3–3 ac AND dc RESISTANCE

The resistance $\Delta V/\Delta I$ is called the *ac* (or *dynamic*) *resistance* of the diode. It is called *ac* resistance because we consider the small *change* in voltage, ΔV, such as might be generated by an ac generator, causing a *change* in current, ΔI. In using this graphical method to calculate the ac resistance, the changes ΔV and ΔI must be kept small enough to avoid covering sections of the *I–V* curve over which there is an appreciable change in slope.

Henceforth we will refer to the ac resistance of the diode as r_D, where the lowercase *r* is in keeping with the convention of using lowercase letters for ac quantities. Thus, let us define r_D as

$$r_D \equiv \frac{\Delta V_D}{\Delta I_D} \tag{3-4}$$

for small ΔV_D and ΔI_D about the operating point. For very small variations, $\Delta I_D/\Delta V_D$ approaches the slope of the tangent at the *Q*-point.

When a dc voltage is applied across a diode, a certain dc current will flow through it. The *dc resistance* of a diode is found by dividing the dc voltage across it by the dc current through it. Thus the dc resistance, also called the *static* resistance, is found by direct application of Ohm's law. We will designate dc diode resistance by R_D:

$$R_D = \frac{V_D}{I_D} \tag{3-5}$$

Like ac resistance, the dc resistance of a diode depends on the point on the *I–V* curve at which it is calculated. For instance, the dc resistance of the diode at point *A* in Figure 3–2 is represented by a straight line that passes through the origin and point *A*. If the diode is biased at a larger current, it is apparent that the straight line will have a larger (steeper) slope, meaning that the dc resistance will be smaller. (The larger the slope, the smaller the resistance.) We see that the diode is nonlinear in both the dc and the ac sense; that is, both its dc and ac resistances change over a wide range.

When analyzing or designing diode circuits, it is often the case that the *I–V* characteristic curve is not available. In most practical work, the ac resistance of a diode is not calculated graphically but is found using a widely accepted approximation. It can be shown that the ac resistance is closely approximated by $r_D \equiv V_T/I_D$, where V_T is the thermal voltage and I_D is the dc current in amperes. For $T = 300$ K, V_T is about 26 mV so at room temperature

$$r_D \approx \frac{26\text{ mV}}{I_D} \tag{3-6}$$

This approximation is valid for both silicon and germanium diodes and is obtained using calculus by differentiating the diode equation

$$I_D \approx I_S e^{V_D/V_T} \tag{3-7}$$

with respect to V_D; that is,

$$\frac{dI_D}{dV_D} = \frac{I_S}{V_T}e^{V_D/V_T} = \frac{I_D}{V_T} = \frac{1}{r_D} \quad \text{or} \quad r_D = \frac{V_T}{I_D} \tag{3-8}$$

There is one additional component of diode resistance that should be mentioned. The resistance of the semiconductor material and the contact resistance where the external leads are attached to the *pn* junction can be lumped together and called the *bulk resistance*, r_B, of the diode. Usually less than 1 Ω, the

bulk resistance also changes with the dc current in the diode, becoming quite small at high current levels. The total ac resistance of the diode is $r_D + r_B$, but at low current levels r_D is so much greater than r_B that r_B can usually be neglected. At high current levels, r_B is typically on the order of 0.1 Ω.

When a diode is connected in a circuit in a way that results in the diode being forward biased, there should always be resistance in series with the diode to limit the current that flows through it. The following example illustrates a practical circuit that could be used to determine *I–V* characteristics.

EXAMPLE 3–1

The circuit shown in Figure 3–3 was connected to investigate the relation between the voltage and current in a certain diode. The adjustable voltage source was set to several different values in order to control the diode current, and the diode voltage was recorded at each setting. The results are tabulated in the table in Figure 3–3.

1. Find the dc resistance of the diode when the voltage across it is 0.56, 0.62, and 0.67 V.
2. Find the ac resistances presented by the diode to an ac signal generator that causes the voltage across the diode to vary between 0.55 V and 0.57 V, between 0.61 V and 0.63 V, and between 0.66 V and 0.68 V.
3. Find the approximate ac resistances when the diode voltages are 0.56 V, 0.62 V, and 0.67 V. Assume bulk resistances of 0.8 Ω, 0.5 Ω, and 0.1 Ω, respectively.

Solution

1. The dc diode resistances at the voltages specified are found from equation 3–5, $R_D = V_D/I_D$. At $V = 0.56$ V,

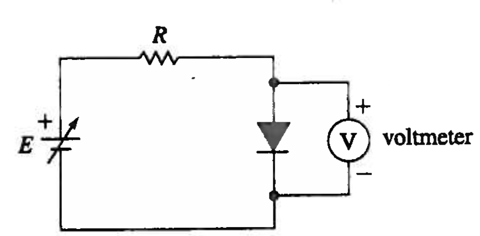
$$R_D = \frac{0.56\ \text{V}}{1.04 \times 10^{-3}\ \text{A}} = 538.5\ \Omega$$

At $V = 0.62$ V,

$$R_D = \frac{0.62\ \text{V}}{10.8 \times 10^{-3}\ \text{A}} = 57.4\ \Omega$$

FIGURE 3–3 (Example 3–1)

Measurement Number	I (mA)	V (volts)
1	0.705	0.55
2	1.04	0.56
3	1.54	0.57
4	7.33	0.61
5	10.8	0.62
6	15.9	0.63
7	51.1	0.66
8	75.3	0.67
9	110.8	0.68



At $V = 0.67$ V,

$$R_D = \frac{0.67\ \text{V}}{75.3 \times 10^{-3}\ \text{A}} = 8.90\ \Omega$$

2. The ac diode resistances are found from equation 3–4, $r_D = \Delta V_D/\Delta I_D$, as follows:

$$r_D = \frac{(0.57 - 0.55)\ \text{V}}{(1.54 - 0.705) \times 10^{-3}\ \text{A}} = \frac{0.02\ \text{V}}{0.835 \times 10^{-3}\ \text{A}} = 23.95\ \Omega$$

$$r_D = \frac{0.02\ \text{V}}{8.57 \times 10^{-3}\ \text{A}} = 2.33\ \Omega$$

$$r_D = \frac{0.02\ \text{V}}{59.7 \times 10^{-3}\ \text{A}} = 0.34\ \Omega$$

3. The approximate ac resistances are found using relation (3–6), $r_D \approx 0.026/I_D$ and adding the bulk resistance r_B. At $V = 0.56$ V,

$$r_D = \frac{0.026}{I_2} + r_B = \frac{0.026}{1.04 \times 10^{-3}\ \text{A}} + 0.8\ \Omega = 25.8\ \Omega$$

At $V = 0.62$ V,

$$r_D = \frac{0.026}{I_5} + r_B = \frac{0.026}{10.8 \times 10^{-3}\ \text{A}} + 0.5\ \Omega = 2.91\ \Omega$$

At $V = 0.67$ V,

$$r_D = \frac{0.026}{I_8} + r_B = \frac{0.026}{75.3 \times 10^{-3}\ \text{A}} + 0.1\ \Omega = 0.445\ \Omega$$

Note that each ac resistance calculated in part 3 is at a diode voltage in the middle of a range (ΔV) over which an ac resistance is calculated in part 2. We can therefore expect the approximations for r_D to agree reasonably well with the values calculated using $r_D = \Delta V_D/\Delta I_D$. The results bear out this fact.

3–4 ANALYSIS OF dc CIRCUITS CONTAINING DIODES

In virtually every practical dc circuit containing a diode, there is one simplifying assumption we can make when the diode current is beyond the knee. We have seen (Figure 3–2, for example) that the *I–V* curve is essentially a vertical line above the knee. *The implication of a vertical line on an I–V characteristic is that the voltage across the device remains constant, regardless of the current that flows through it.* Thus the voltage drop across a diode remains substantially constant for all current values above the knee. This fact is responsible for several interesting applications of diodes. For present purposes, it suggests that the diode is equivalent to another familiar device that has this same property of maintaining a constant voltage, independent of current: a voltage source! Indeed, our first simplified equivalent circuit of a diode is a voltage source having a potential equal to the (essentially) constant drop across it when the current is above the knee.

Figure 3–4(a) shows a simple circuit containing a forward-biased diode. Assuming the current is above the knee, the diode can be replaced by a 0.7-V source as shown in Figure 3–4(b).

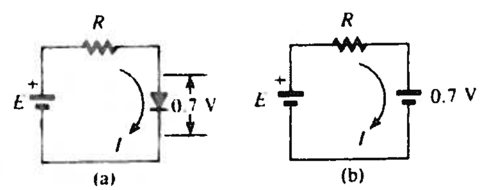


FIGURE 3–4 For analysis purposes, the forward-biased diode in (a) can be replaced by a voltage source, as in (b)

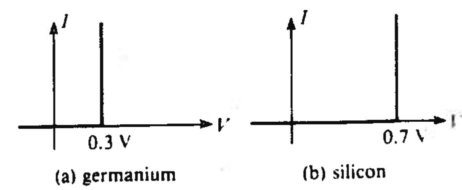


FIGURE 3–5 Idealized characteristic curves. The diodes are assumed to be open circuits until the forward-biasing voltages are reached.

The idealized characteristic curves in Figure 3–5 imply that the diode is an *open* circuit (infinite resistance, zero current) for all voltages less than 0.3 V or 0.7 V and becomes a short circuit (zero resistance) when one of those voltage values is reached. These approximations are quite valid in most real situations. Note that it is not possible to have, say, 5 V across a forward-biased diode. If a diode were connected directly across a +5-V source, it would act like a short circuit and damage either the source, the diode, or both. When troubleshooting a circuit that contains a diode that is supposed to be forward biased, a diode voltage measurement greater than 0.3 V or 0.7 V means that the diode has failed and is in fact open.

In some dc circuits, the voltage drop across a forward-biased diode may be so small in comparison to other dc voltages in the circuit that it can be neglected entirely. For example, suppose a circuit consists of a 25-V source in series with a 1-kΩ resistor in series with a germanium diode. Then $I = (25 - 0.3)/(1\ \text{k}\Omega) = 24.7$ mA. Neglecting the drop across the diode, we would calculate $I = 25/(1\ \text{k}\Omega) = 25$ mA, a result that in most practical situations would be considered close enough to 24.7 mA to be accurate.

EXAMPLE 3–2

Assume that the silicon diode in Figure 3–6 requires a minimum current of 1 mA to be above the knee of its *I–V* characteristic.

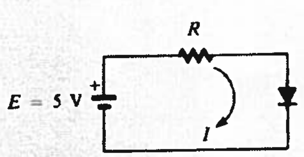


FIGURE 3–6 (Example 3–2)

1. What should be the value of R to establish 5 mA in the circuit?
2. With the value of R calculated in (1), what is the minimum value to which the voltage E could be reduced and still maintain diode current above the knee?

Solution

1. If I is to equal 5 mA, we know that the voltage across the diode will be 0.7 V. Therefore, solving for R,

$$R = \frac{E - 0.7}{I} = \frac{(5 - 0.7)\ \text{V}}{5 \times 10^{-3}\ \text{A}} = 860\ \Omega$$

2. In order to maintain the diode current above the knee, I must be at least 1 mA. Thus,

$$I = \frac{E - 0.7}{R} \geq 10^{-3}\ \text{A}$$

Therefore, since $R = 860\ \Omega$,

$$\frac{E - 0.7}{860} \geq 10^{-3}\ \text{A}$$

or

$$E \geq (860 \times 10^{-3}) + 0.7$$
$$E \geq 1.56\ \text{V}$$

Circuits containing dc sources and two or more diodes can be analyzed through general circuit analysis by assuming a conducting or nonconducting state for each diode according to the polarity or orientation of the sources. Each diode assumed to be conducting is replaced by a 0.7-V or 0.3-V source. Even in cases where the conduction state is not obvious, one can assume an arbitrary state and solve for the currents. If a diode is assumed to be forward biased and the calculated forward current turns out to be negative, it means that the diode is not conducting and should be replaced by an open circuit. Obviously, the circuit needs to be reanalyzed with the new condition. An example illustrating the concept follows.

EXAMPLE 3–3

Determine the current through each branch in the following circuit (Figure 3–7). Assume silicon diodes.

Solution

Assuming both diodes are conducting, we replace both with 0.7-V sources as indicated in Figure 3–8 and write the two mesh equations according to the assigned directions for I_1 and I_2.

$$\text{Mesh 1:}\quad 3I_1 - 2I_2 = 13.6\ \text{(using V, k}\Omega\text{, and mA)}$$
$$\text{Mesh 2:}\quad -2I_1 + 5I_2 = -4.3$$

Using Kramer's rule or any of the other methods, we obtain

$$I_1 = 5.4\ \text{mA} = I_{D1} \text{ and } I_2 = 1.3\ \text{mA}$$

The (forward) current through D_2, according to KCL, is then

$$I_{D2} = 5.4 - 1.3 = 4.1\ \text{mA}$$

Because both diode currents turned out to be positive, both diodes are indeed conducting and the answers are all correct.

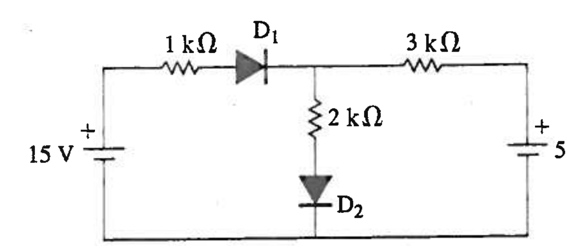


FIGURE 3–7 (Example 3–3)

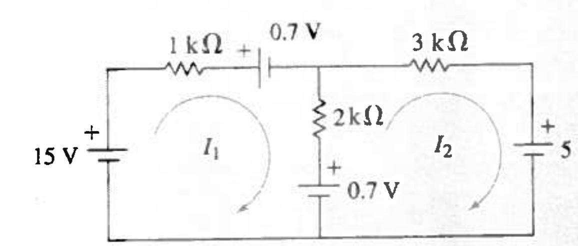


FIGURE 3–8 (Example 3–3)

EXAMPLE 3–4

Sketch the output voltage V_o in the following circuit for the variable input voltage V_S depicted in Figure 3–9.

Solution

When $V_S = 0$, the diode is reverse biased and is therefore an open circuit. The output voltage at this point is also zero. As V_S increases, the diode will continue being open and V_o will be equal to, or track, V_S since no drop occurs across the

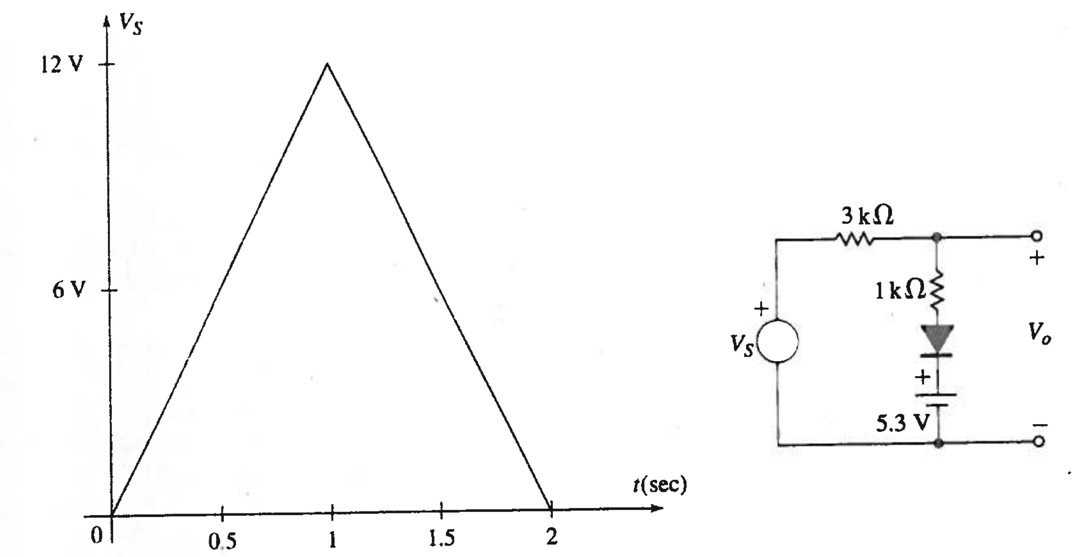


FIGURE 3–9 (Example 3–4)

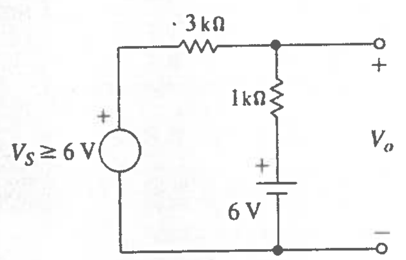


FIGURE 3–10 (Example 3–4)

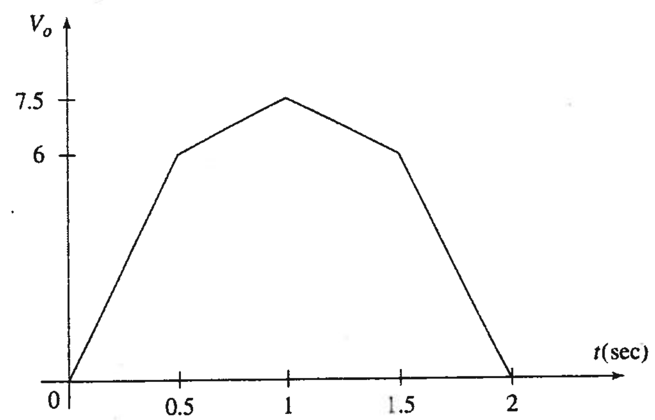


FIGURE 3–11 (Example 3–4)

series resistor. The diode starts conducting at $t = 0.5$ sec when $V_S = 6$ V, that is, when it overcomes the 5.3-V battery plus the 0.7-V diode drop. When the diode is conducting, the equivalent circuit in Figure 3–10 results.

Using superposition and the voltage-division rule, we can write (using V, mA, and kΩ) an expression for V_o as a function of V_S:

$$V_o = \left(\frac{1}{1+3}\right)V_S + \left(\frac{3}{1+3}\right)6 = 0.25\ V_S + 4.5\ \ (V_S \geq 6\ \text{V})$$

Alternatively, we could have written the loop current $I = (V_S - 6)/4$, from which we obtain the voltage V_o as

$$V_o = I(1) + 6 = \frac{V_S - 6}{4} + 6 = 0.25\ V_S + 4.5\ \text{V}\ \ (V_S \geq 6\ \text{V})$$

According to this expression, when $V_S = 6$ V at $t = 0.5$ sec, $V_o = 0.25(6) + 4.5 = 6$ V, as expected. At $t = 1$ sec, when $V_S = 12$ V, V_o is $0.25(12) + 4.5 = 7.5$ V. Using symmetry, we can determine the behavior of the circuit for $1 \leq t \leq 2$. The resulting waveform for V_o is illustrated in Figure 3–11.

The Load Line

The concept of biasing a diode by means of a voltage source and a series resistor can also be seen from a graphical perspective. In later chapters, we will see that this graphical analysis applies to other devices as well. Consider the diode circuit of Figure 3–12. According to KVL, the loop equation yields $I_D = (E - V_D)/R = -(1/R)V_D + E/R$. Note that this equation is a straight line (recall $y = mx + b$) with slope $-1/R$ and y-intercept (I_D-intercept, in our case) E/R. The relationship between V_D and I_D also obeys the diode equation, namely:

$$I_D \approx I_s e^{V_D/V_T} \tag{3–9}$$

So if we plot both the straight line and the exponential diode curve as shown in Figure 3–12, the crossing point will clearly represent the simultaneous solution of the two equations. The coordinates of this point are the operating voltage and current of the diode for the given E and R values, that is, the biasing operating point (Q-point). If the resistor R is reduced in value, the slope of the straight line will be steeper (dotted line) with the crossing point at a higher current as expected.

To further illustrate the point, suppose we wanted to reduce the current back to its original value but now by reducing the source voltage E. This effect can also be seen graphically as the shifting of the straight line to the left while maintaining the same slope (same resistance) as shown in the figure.

The process just described dealt with changing the resistance or the source voltage to change the operating point. Now let us look at what happens if, for instance, the diode is exposed to higher temperatures. As we know, the diode drop decreases at a rate of approximately −2.2 mV/°C. Figure 3–12 shows how the operating point moves according to the shifting of the diode curve due to change in temperature. As temperature increases, V_{DQ} decreases and I_{DQ} increases. In this situation, of course, we are not dealing with changing the operating point for design purposes, but with the undesirable effect of having the operating point displaced due to changes in temperature.

3–5 ELEMENTARY POWER SUPPLIES

A typical application of diodes is in the construction of *dc power supplies*, which are electronic circuits that convert ac voltage to dc voltage, or dc voltage to a different dc voltage. Every electronic apparatus needs a power supply to operate. In this section, we will learn about the different basic schemes of obtaining dc voltage from an ac voltage source, such as a 120-V household outlet.

We will first look at the behavior of a diode when it is operated under *large-signal* conditions, that is, when the current and voltage changes it undergoes extend over a large portion of its characteristic curve, from full conduction to reverse biasing and vice versa. When this is the case, the diode resistance will change between very small and very large values and, for all practical purposes, the diode will behave very much like a *switch*.

An ideal (perfect) switch has zero resistance when closed and infinite resistance when open. Similarly, an *ideal* diode for large-signal applications is one whose resistance changes between these same two extremes. When analyzing such circuits, it is often helpful to think of the diode as a *voltage-controlled switch:* A forward-biasing voltage closes it, and a zero or reverse-biasing voltage opens it. Depending on the magnitudes of other voltages in the circuit, the 0.3-

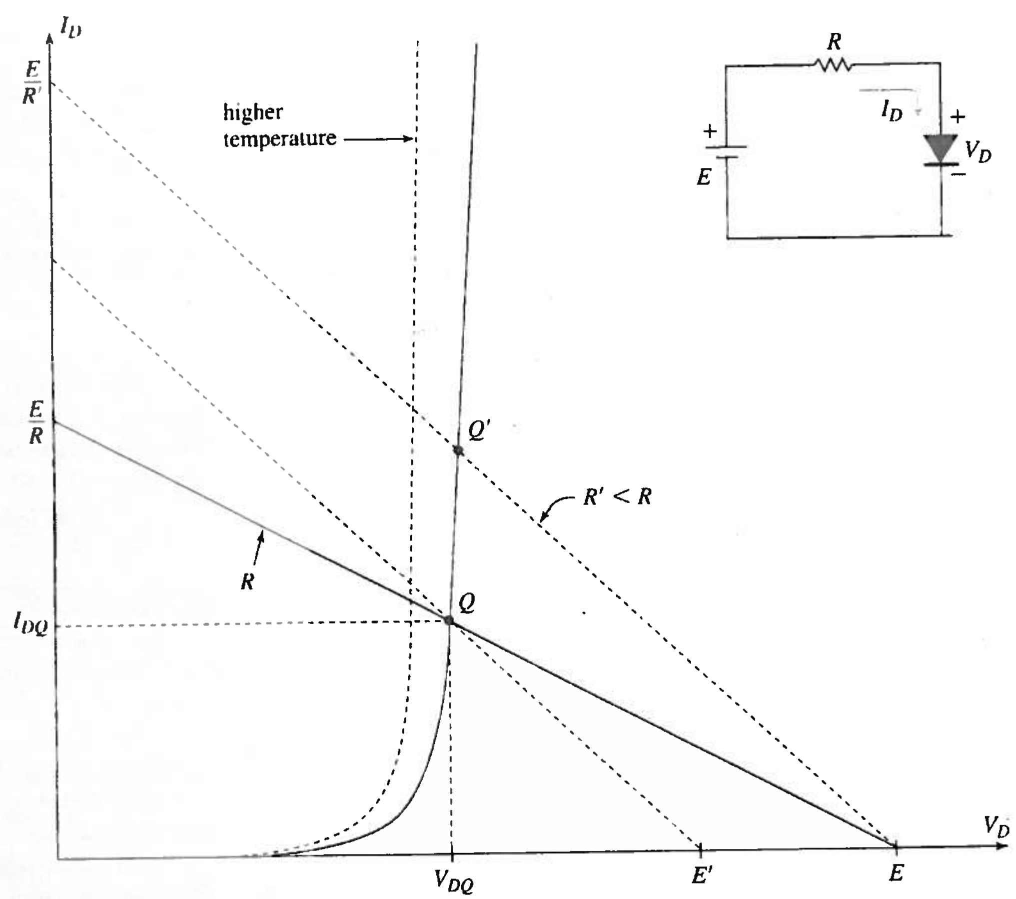


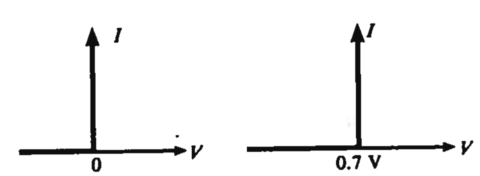
FIGURE 3–12 Q point displacement due to changes in load line and temperature

or 0.7-V drop across the diode when it is forward biased may or may not be negligible. Figure 3–13 shows the idealized characteristic curve for a silicon diode (a) when the 0.7-V drop is neglected and (b) when it is not. In case (a), the characteristic curve is the same as that of a perfect switch.

Half-Wave and Full-Wave Rectifiers

One of the most common uses of a diode in large-signal operation is in a *rectifier* circuit. A rectifier is a device that permits current to flow through it in one direction only. It is easy to see how a diode performs this function when we think of it as a voltage-controlled switch. When the anode voltage is positive with respect to the cathode, i.e., when the diode is forward biased, the "switch is closed" and current flows through it from anode to cathode. If the anode becomes negative with respect to the cathode, the "switch is open"

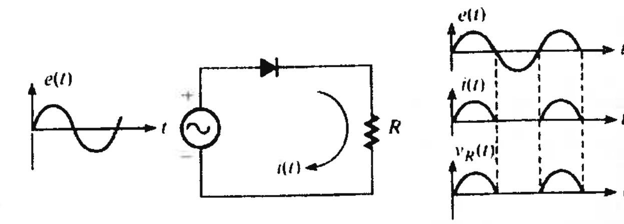
FIGURE 3–13 Idealized silicon diode characteristics, used for large-signal analysis



(a) I–V characteristic when the diode is treated as a perfect switch having 0 voltage drop.

(b) I–V characteristic when the diode is treated as a perfect switch that closes when V = 0.7 volts.

FIGURE 3–14 The diode used as a rectifier. Current flows only during the positive half-cycle of the input.



and no current flows. Of course, a *real* diode is not perfect, so there is in fact some very small reverse current that flows when it is reverse biased. Also, as we know, there is a nonzero voltage drop across the diode when it is forward biased (0.3 or 0.7 V), a drop that would not exist if it were a perfect switch.

Consider the rectifier circuit shown in Figure 3–14. We see in the figure that an ac voltage source is connected across a diode and a resistor, R, the latter designed to limit current flow when the diode is forward biased. Notice that no dc source is present in the circuit. Therefore, during each positive half-cycle of the ac source voltage $e(t)$, the diode is forward biased and current flows through it in the direction shown. During each negative half-cycle of $e(t)$ the diode is reverse biased and no current flows. The waveforms of $e(t)$ and $i(t)$ are sketched in the figure. We see that $i(t)$ is a series of positive current pulses separated by intervals of zero current. Also sketched is the waveform of the voltage $v_R(t)$ that is developed across R as a result of the current pulses that flow through it. Note that the net effect of this circuit is the conversion of an ac voltage into a pulsating dc voltage, a fundamental step in the construction of a dc *power supply*.

If the diode in the circuit of Figure 3–14 is turned around so that the anode is connected to the resistor and the cathode to the generator, then the diode will be forward biased during the negative half-cycles of the sine wave. The current would then consist of a sequence of pulses representing current flow in a counterclockwise, or negative, direction around the circuit.

EXAMPLE 3–5

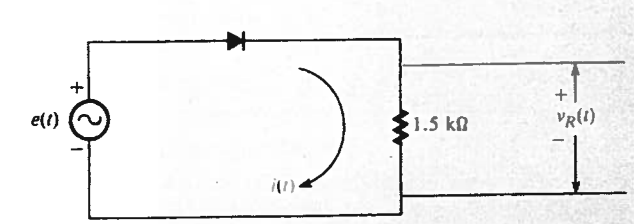
Assume that the silicon diode in the circuit of Figure 3–15 has a characteristic like that shown in Figure 3–13(b). Find the peak values of the current $i(t)$ and the voltage $v_R(t)$ across the resistor when

1. $e(t) = 20 \sin \omega t$, and
2. $e(t) = 1.5 \sin \omega t$. In each case, sketch the waveforms for $e(t)$, $i(t)$, and $v_R(t)$.

Solution

1. When $e(t) = 20 \sin \omega t$, the peak positive voltage generated is 20 V. At the instant $e(t) = 20$ V, the voltage across the resistor is $20 - 0.7 = 19.3$ V, and the current is $i = 19.3/(1.5\text{ k}\Omega) = 12.87$ mA. Figure 3–16 shows the resulting waveforms. Note that because of the characteristic assumed in Figure 3–13(b), the diode does not begin conducting until $e(t)$ reaches +0.7 V and ceases conducting when $e(t)$ drops below 0.7 V. The time interval between the point where $e(t) = 0$ V and $e(t) = 0.7$ V is very short in comparison to the half-cycle of conduction time. From a practical

FIGURE 3–15 (Example 3-5)



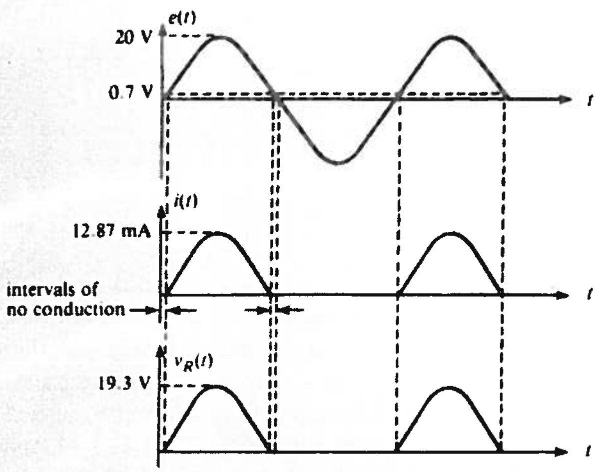


FIGURE 3–16 Diode current and voltage in the circuit of Figure 3–15. Note that the diode does not conduct until $e(t)$ reaches 0.7 V, so short intervals of nonconduction occur during each positive half-cycle.

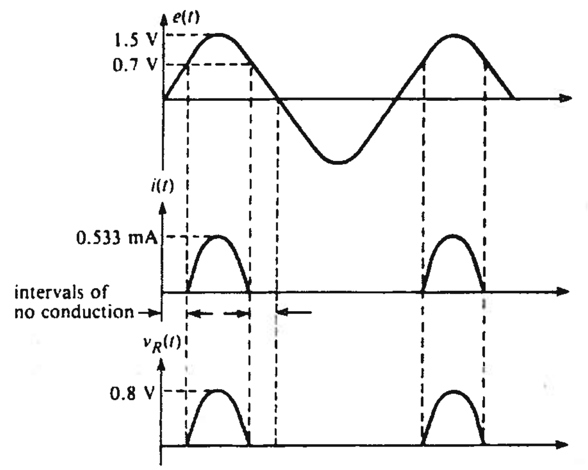


FIGURE 3–17 Diode current and voltage in the circuit of Figure 3–15 when the sine wave peak is reduced to 1.5 V. Note that the intervals of nonconduction are much longer than those in Figure 3–16.

standpoint, we could have assumed the characteristic in Figure 3–13(a), i.e., neglected the 0.7-V drop, and the resulting waveforms would have differed little from those shown.

2. When $e(t) = 1.5 \sin \omega t$, the peak positive voltage generated is 1.5 V. At that instant, $v_R(t) = 1.5 - 0.7 = 0.8$ V and $i(t) = (0.8\text{ V})/(1.5\text{ k}\Omega) = 0.533$ mA. The waveforms are shown in Figure 3–17. Note once again that the diode does not conduct until $e(t) = 0.7$ V. However, in this case, the time interval between $e(t) = 0$ V and $e(t) = 0.7$ V is a significant portion of the conducting cycle. Consequently, current flows in the circuit for significantly less time than one-half cycle of the ac waveform. In this case, it clearly would *not* be appropriate to use Figure 3–13(a) as an approximation for the characteristic curve of the diode.

As already mentioned, an important application of diodes is in the construction of dc power supplies. It is instructive at this time to consider how diode rectification and waveform filtering, the first two operations performed by every power supply, are used to create an elementary dc power source.

The single-diode circuit in Figure 3-14 is called a *half-wave* rectifier, because the waveforms it produces ($i(t)$ and $v_R(t)$) each represent half a sine wave. These half-sine waves are a form of pulsating dc and by themselves are of little practical use. (They can, however, be used for charging batteries, an application in which a steady dc current is not required.)

Capacitive Filtering

Most practical electronic circuits require a dc voltage source that produces and maintains a *constant* voltage. For that reason, the pulsating half-sine waves must be converted to a steady dc level. This conversion is accomplished by *filtering* the waveforms. Filtering is a process in which selected frequency components of a complex waveform are *rejected* (filtered out) so that they do not appear in the output of the device (the filter) performing the filtering operation. The pulsating half-sine waves (like all periodic waveforms) can be regarded as waveforms that have both a dc component and ac components.

Our purpose in filtering these waveforms for a dc power supply is to reject *all* the ac components. It can be shown that the average (or dc) value of a half-wave rectified waveform is given by

$$V_{avg} = \frac{V_{PR}}{\pi} \quad \text{(half-wave)} \tag{3-10}$$

where V_{PR} = peak value of the rectified waveform = $\sqrt{2}V_{rms} - 0.7$ V.

This average or dc value is what a dc voltmeter would read when connected across the load resistor.

The simplest kind of filter that will perform the filtering task we have just described is a capacitor. Recall that a capacitor has reactance inversely proportional to frequency: $X_C = 1/2\pi fC$. Thus, if we connect a capacitor directly across the output of a half-wave rectifier, the ac components will "see" a low-impedance path to ground and will not, therefore, appear in the output. Figure 3–18 shows a filter capacitor, C, connected in this way. In this circuit the capacitor charges to the peak value of the rectified waveform, V_{PR}, so the output is the dc voltage V_{PR}. Note that $V_{PR} = V_P - V_D$, where V_P is the peak value of the sinusoidal input and V_D is the dc voltage drop across the diode (0.7 V for silicon).

In practice, a power supply must provide dc current to whatever load it is designed to serve, and this load current causes the capacitor to discharge and its voltage to drop. The capacitor discharges during the intervals of time between input pulses. Each time a new input pulse occurs, the capacitor recharges. Consequently, the capacitor voltage rises and falls in synchronism with the occurrence of the input pulses. These ideas are illustrated in Figure 3–19. The output waveform is said to have a *ripple voltage* superimposed on its dc level, V_{dc}.

When the peak-to-peak value of the output ripple voltage, V_{PP}, is small compared to V_{dc}, (a condition called *light loading*), we can assume that the load current is essentially constant and will discharge the capacitor linearly according to the basic equation

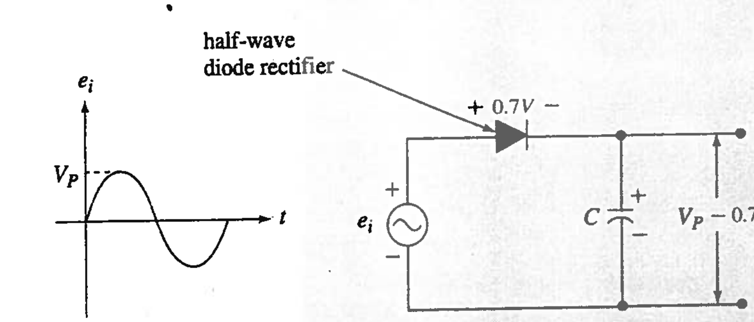
$$\Delta V = \frac{I\Delta t}{C} \tag{3-11}$$

where ΔV is the reduction in capacitor voltage over the time interval Δt and I is the current discharging the capacitor. Notice that Δt, within our discussion, is very close to the period of the rectified waveform; therefore, replacing ΔV with V_{PP}, we can write the following expression:

$$V_{PP} = \frac{I_L}{f_r C} = \frac{V_{dc}}{f_r R_L C} \tag{3-12}$$

where I_L = load current
f_r = frequency of the rectified waveform
C = filter capacitance

FIGURE 3–18 Filter capacitor C effectively removes the ac components from the half-wave rectified waveform.



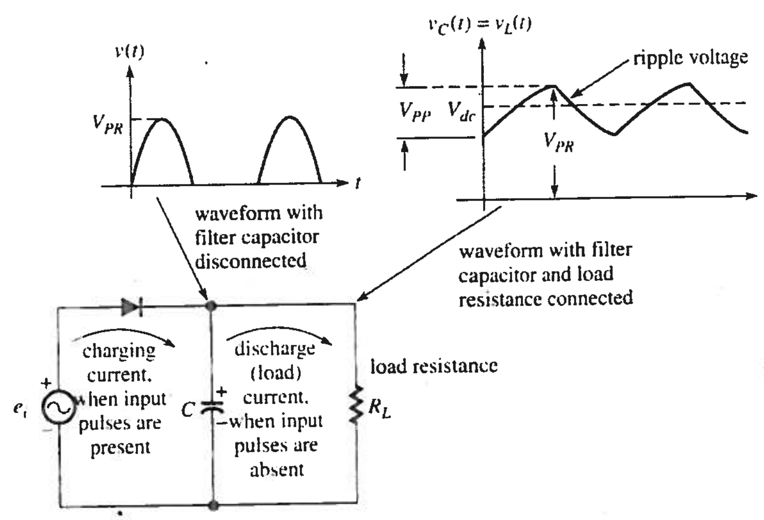


FIGURE 3–19 When load resistance R_L is connected across the filter capacitor, the capacitor charges and discharges, creating a load voltage that has a ripple voltage superimposed on a dc level.

The dc voltage across the load is the average of the maximum and minimum values caused by the ripple voltage. This can clearly be approximated as the maximum value minus one half of V_{PP}, expressly

$$V_{dc} = V_{PR} - \frac{V_{PP}}{2} \tag{3-13}$$

or

$$V_{dc} = V_{PR} - \frac{I_L}{2f_rC} \tag{3-14}$$

Note that this form is expressed in terms of I_L, which is the most general situation. However, in the case where the load is a fixed resistance R_L, I_L can be replaced with V_{dc}/R_L, yielding

$$V_{dc} = \frac{V_{PR}}{1 + \dfrac{1}{2f_rR_LC}} \tag{3-15}$$

Observing a rectified and filtered waveform, it is obvious that the smaller the variation V_{PP}, the more the waveform will resemble a pure dc voltage. The variation portion is known as *ripple* and the value V_{PP} is known as the *ripple voltage*. Furthermore, the ratio of the ripple voltage to the dc or average voltage is known as the *ripple factor* or *percent ripple* and represents a measure of how close the filtered waveform resembles a dc voltage. Obviously, low ripple factors are desirable and can be achieved by properly selecting the capacitor value. The ripple factor r is then expressed by

$$r = \frac{V_{PP}}{V_{dc}} \times 100\%$$

Ripple factors of up to 10% are typically acceptable in noncritical applications. However, precision electronic circuits could require supply voltages with very low ripple factors. Although ripple factors could be reduced arbitrarily by using large capacitor values, a more practical solution is to use special circuits called *voltage regulators* that not only reduce the ripple voltage substantially but also maintain a constant dc voltage under variable load current. These circuits will be addressed later in the chapter.

EXAMPLE 3–6

The sinusoidal input, e_i, in Figure 3–19 is 120 V rms and has frequency 60 Hz. The load resistance is 2 kΩ and the filter capacitance is 100 μF. Assuming light loading and neglecting the voltage drop across the diode,

1. find the dc value of the load voltage;
2. find the peak-to-peak value of the ripple voltage.

Solution

1. The peak value of the sinusoidal input voltage is $V_P = \sqrt{2}\,(120 \text{ V rms}) = 169.7$ V. Since the voltage drop across the diode can be neglected, $V_{PR} = V_P = 169.7$ V. From equation 3–15,

$$V_{dc} = \frac{169.7 \text{ V}}{1 + \dfrac{1}{2(60 \text{ Hz})(2 \text{ k}\Omega)(100\ \mu\text{F})}} = 162.9 \text{ V}$$

2. From equation 3–12,

$$V_{PP} = \frac{162.9 \text{ V}}{(60 \text{ Hz})(2 \text{ k}\Omega)(100\ \mu\text{F})} = 13.57 \text{ V}$$

Full-Wave Rectification

A *full-wave* rectifier effectively inverts the negative half-pulses of a sine wave to produce an output that is a sequence of positive half-pulses with no intervals between them. Figure 3–20 shows a widely used full-wave rectifier constructed from four diodes and called a full-wave diode *bridge*. Also shown is the full-wave rectified output. In this case, the average or dc value of the rectified waveform is

$$V_{avg} = \frac{2}{\pi}V_{PR} \quad \text{(full-wave)} \tag{3-16}$$

Note that on each half-cycle of input, current flows through *two* diodes, so the peak value of the rectified output is $V_{PR} = V_P - 2V_D$ or $V_P - 1.4$ V for silicon.

As in the half-wave rectifier, the full-wave rectified waveform can be filtered by connecting a capacitor in parallel with load R_L. The advantage of the full-wave rectifier is that the capacitor does not discharge so far between input pulses, because a new charging pulse occurs every half-cycle instead of every full cycle. Consequently, the magnitude of the output ripple voltage is smaller. This fact is illustrated in Figure 3–21.

Equations 3–12 and 3–14 for V_{PP} and V_{dc} are valid for both half-wave and full-wave rectifiers. Note that f_r in those equations is the frequency of the *rectified* waveform, which, in a full-wave rectifier, is *twice* the frequency of the

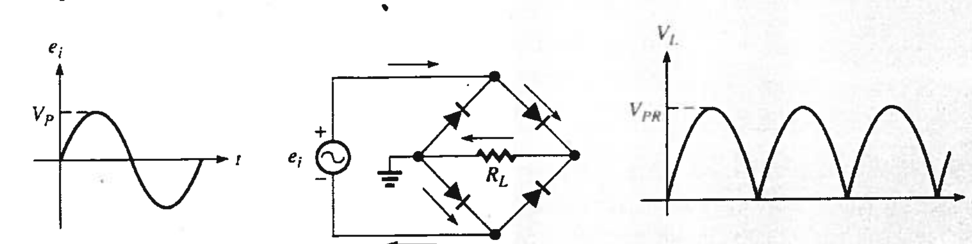
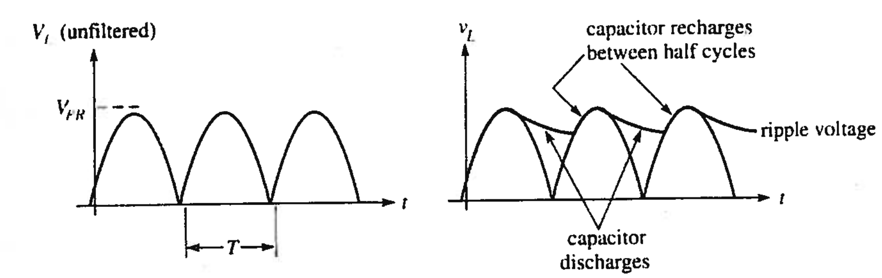


FIGURE 3–20 The full-wave bridge rectifier and output waveform. The arrows show the direction of current flow when e_i is positive.

FIGURE 3-21 The ripple voltage in the filtered output of a full-wave rectifier is smaller than in the half-wave case because the capacitor recharges at shorter intervals.



unrectified sine wave (see Figure 3-21). If the same input and component values used in Example 3-6 are used to compute V_{dc} and V_{PP} for a full-wave rectifier (f_r = 120 Hz), we find

$$V_{dc} = \frac{169.7\text{ V}}{1 + \dfrac{1}{2(120\text{ Hz})(2\text{ k}\Omega)(100\ \mu\text{F})}} = 166.2\text{ V}$$

and

$$V_{PP} = \frac{166.2\text{ V}}{(120\text{ Hz})(2\text{ k}\Omega)(100\ \mu\text{F})} = 6.92\text{ V}$$

Note that the value of the ripple voltage is one-half that found for the half-wave rectifier.

Another means of obtaining full-wave rectification is through a center-tapped transformer and two diodes, as shown in Figure 3-22. Assume that the transformer is wound so that terminal A on the secondary is positive with respect to terminal B at an instant of time when v_{in} is positive, as signified by the polarity symbols (dot convention) shown in the figure. Then, with the center tap as reference (ground), v_A is positive with respect to ground and v_B is negative with respect to ground. Similarly, when v_{in} is negative, v_A is negative with respect to ground and v_B is positive with respect to ground.

Figure 3-22(b) shows that when v_{in} is positive, v_A forward biases diode D_1. As a consequence, current flows in a clockwise loop through R_L. Figure 3-22(c) shows that when v_{in} is negative, D_1 is reverse biased, D_2 is forward biased, and current flows through R_L in a counterclock-wise loop. Notice that the voltage developed across R_L has the same polarity in either case. Therefore, positive voltage pulses are developed across R_L during both the positive and negative half-cycles of v_{in}, and a full-wave-rectified waveform is created.

The peak rectified voltage is the secondary voltage in the transformer, between center tap and one side, less the diode drop:

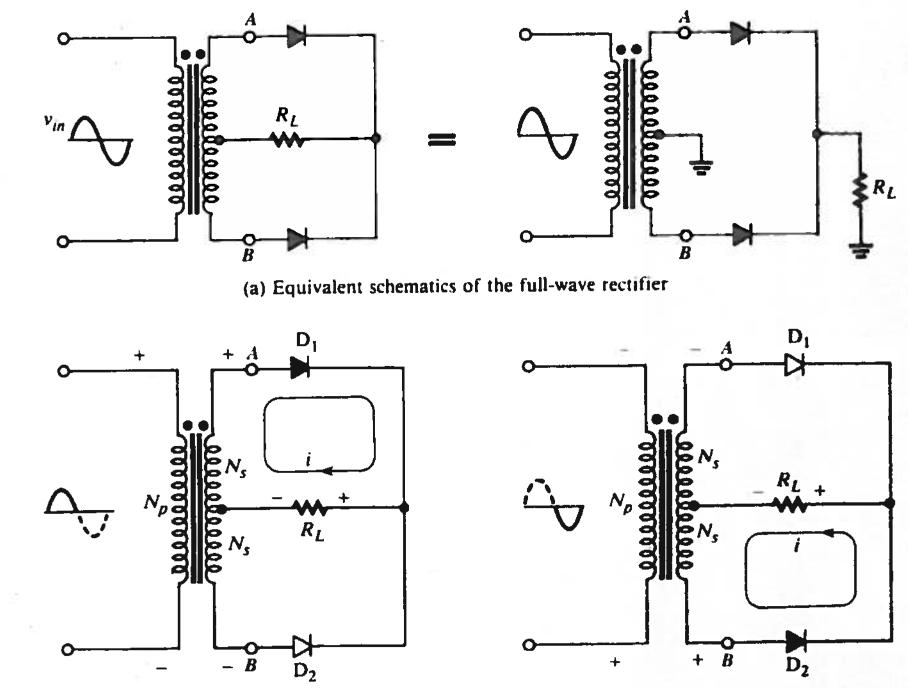
$$V_{PR} = V_P - 0.7\text{ V} \tag{3-17}$$

where V_P is the peak secondary voltage per side.

To determine the maximum reverse bias to which each diode is subjected, refer to the circuit in Figure 3-23. Here, we show the voltage drops in the rectifier when diode D_1 is forward biased and diode D_2 is reverse biased. Neglecting the 0.7-V drop across D_1, the voltage across R_L is v_A volts. Thus the cathode-to-ground voltage of D_2 is v_A volts. Now, the anode-to-ground voltage of D_2 is $-v_B$ volts, as shown in the figure. Therefore, the total reverse bias across D_2 is $v_A + v_B$ volts, as shown. When v_A is at its positive peak, v_B is at its negative peak, so the maximum reverse bias equals *twice* the peak value of either. We conclude that the PIV *(peak inverse voltage)* rating of each diode must be equal to at least twice the peak value of the rectified voltage:

$$\text{PIV} \geq 2V_{PR}$$

FIGURE 3-22 A full-wave rectifier employing a center-tapped transformer and two diodes

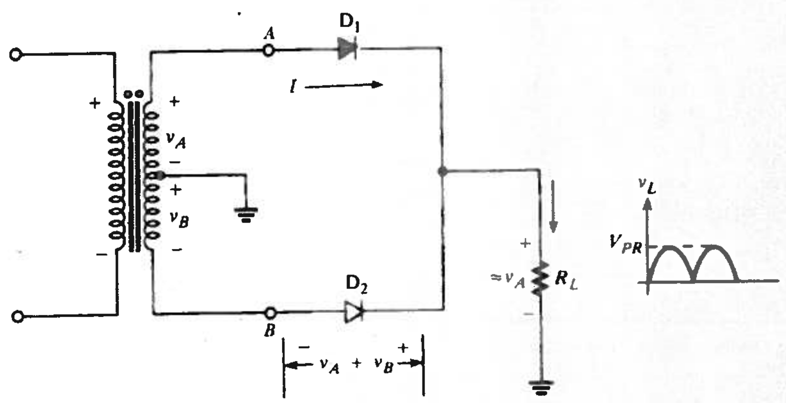


(a) Equivalent schematics of the full-wave rectifier

(b) Current flow when v_{in} is positive. D_1 is forward biased and D_2 is reverse biased.

(c) Current flow when v_{in} is negative. D_1 is reverse biased and D_2 is forward biased.

FIGURE 3-23 Diode D_2 is reverse biased by $v_A + v_B$ volts, which has a maximum value of $2V_{PR}$ volts



EXAMPLE 3-7

The primary voltage in the circuit shown in Figure 3-24 is 120 V rms, and the secondary voltage is 60 V rms from side to side (60 VCT). Find

1. the average value of the voltage across R_L;
2. the (approximate) average power dissipated by R_L; and
3. the minimum PIV rating required for each diode.

Solution

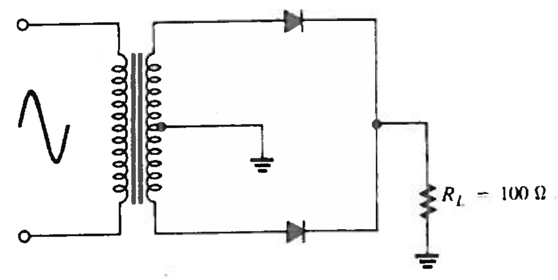
1. $V_P = \sqrt{2}(30) = 42.4$ V per side

   From equation 3-17, $V_{PR} = V_P - 0.7\text{ V} = 42.4 - 0.7\text{ V} = 41.7$ V.

   Although equation 3-16 does not strictly apply to a rectified waveform with 0.7-V nonconducting gaps, it is a good approximation when the peak value is so much greater than 0.7 V:

$$V_{avg} \approx \frac{2V_{PR}}{\pi} = \frac{2(41.7\text{ V})}{\pi} = 26.5\text{ V}$$

FIGURE 3-24 (Example 3-7)



2. $V_{rms} = \dfrac{V_{PR}}{\sqrt{2}} = \dfrac{41.7\text{ V}}{\sqrt{2}} = 29.5\text{ V rms}$

$P_{avg} = \dfrac{V_{rms}^2}{R_L} = \dfrac{(29.5\text{ V})^2}{100\ \Omega} = 8.7\text{ W}$

3. $\text{PIV} \geq 2V_{PR} = 2(41.7) = 83.4\text{ V}$

Capacitive filtering with the center-tap configuration is identical to that described for the diode-bridge circuit. The only difference is the peak voltage of the rectified waveform which, in this case, involves only one diode drop. Remember that in this configuration, the circuit rectifies the voltage from the center tap to each side of the transformer in alternating half-cycles. For example, if the secondary of a transformer is rated 18 VCT, meaning 18 volts rms with a center tap, the peak voltage of the rectified waveform V_{PR} will be $9 \times 1.414 - 0.7$, or about 12 V.

Although the elementary power supplies we have described can be used in applications where the presence of some ripple voltage is acceptable, where the exact value of the output voltage is not critical, and where the load does not change appreciably, more sophisticated power supplies have more elaborate filters and special circuitry (voltage regulators) that maintain a constant output voltage under a variety of operating conditions. These refinements are discussed in detail in Chapter 13.

Voltage Multipliers

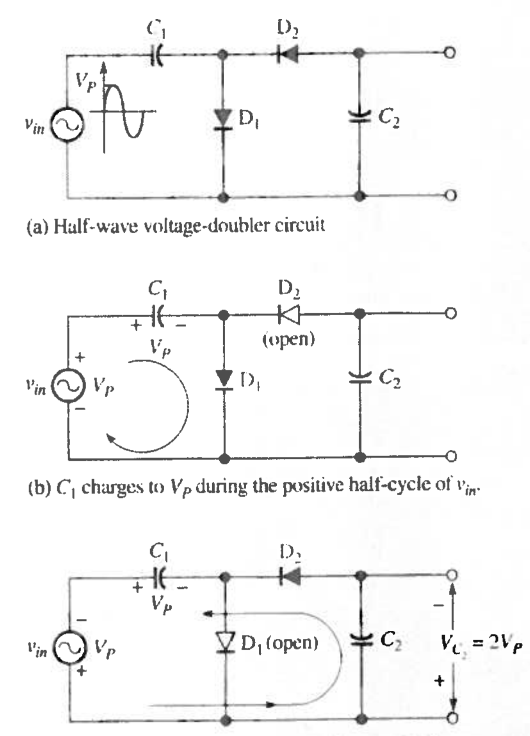
Diodes and capacitors can be connected in various configurations to produce filtered, rectified voltages that are integer multiples of the peak value of an input sine wave. By using a transformer to change the amplitude of an ac voltage before it is applied to a voltage multiplier, a wide range of dc levels can be produced using this technique. One advantage of a voltage multiplier is that high voltages can be obtained without using a high-voltage transformer.

HALF-WAVE VOLTAGE DOUBLER Figure 3–25(a) shows a half-wave voltage *doubler*. When v_{in} first goes positive, diode D_1 is forward biased and diode D_2 is reverse biased. Because the forward resistance of D_1 is quite small, C_1 charges rapidly to V_P (neglecting the diode drop), as shown in (b). During the ensuing negative half-cycle of v_{in}, D_1 is reverse biased and D_2 is forward biased, as shown in (c). Consequently, C_2 charges rapidly, with polarity shown. Neglecting the drop across D_2, we can write Kirchhoff's voltage law around the loop at the instant v_{in} reaches its negative peak, and obtain

$$V_P = -V_P + V_{C_2}$$

or

FIGURE 3-25 A half-wave voltage doubler



(a) Half-wave voltage-doubler circuit

(b) C_1 charges to V_P during the positive half-cycle of v_{in}.

(c) C_2 charges to $2V_P$ during the negative half-cycle of v_{in}

$$V_{C_2} = 2V_P \tag{3-18}$$

During the next positive half-cycle of v_{in}, D_2 is again reverse biased and the voltage across the output terminals remains at $V_{C_2} = 2V_P$ volts. Note carefully the polarity of the output. If a load resistor is connected across C_2, then C_2 will discharge into the load during positive half-cycles of v_{in} and will recharge to $2V_P$ volts during negative half-cycles, creating the usual ripple waveform. The PIV rating of each diode must be at least $2V_P$ volts.

FULL-WAVE VOLTAGE DOUBLER Figure 3–26(a) shows a full-wave voltage doubler. This circuit is the same as the full-wave bridge rectifier shown in Figure 3–20, with two of the diodes replaced by capacitors. When v_{in} is positive, D_1 conducts and C_1 charges to V_P volts, as shown in (b). When v_{in} is negative, D_2 conducts and C_2 charges to V_P volts, with the polarity shown in (c). It is clear that the output voltage is then $V_{C_1} + V_{C_2} = 2V_P$ volts. Since one or the other of the capacitors is charging during every half-cycle, the output is the same as that of a capacitor-filtered, full-wave rectifier. Note, however, that the effective filter capacitance is that of C_1 and C_2 in series, which is less than either C_1 or C_2. The PIV rating of each diode must be at least $2V_P$ volts.

VOLTAGE TRIPLER AND QUADRUPLER By connecting additional diode-capacitor sections across the half-wave voltage doubler, output voltages equal to three and four times the input peak voltage can be obtained. The circuit is shown in Figure 3–27. When v_{in} first goes positive, C_1 charges to V_P through forward-biased diode D_1. On the ensuing negative half-cycle, C_2 charges through D_2 and, as demonstrated earlier, the voltage across C_2 equals $2V_P$. During the next positive half-cycle, D_3 is forward biased and C_3 charges to the same voltage attained by C_2: $2V_P$ volts. On the next negative half-cycle, D_2 and D_4 are forward biased and C_4 charges to $2V_P$ volts. As shown in the figure, the voltage across the combination of C_1 and C_3 is $3V_P$ volts, and that across C_2 and C_4 is $4V_P$ volts.

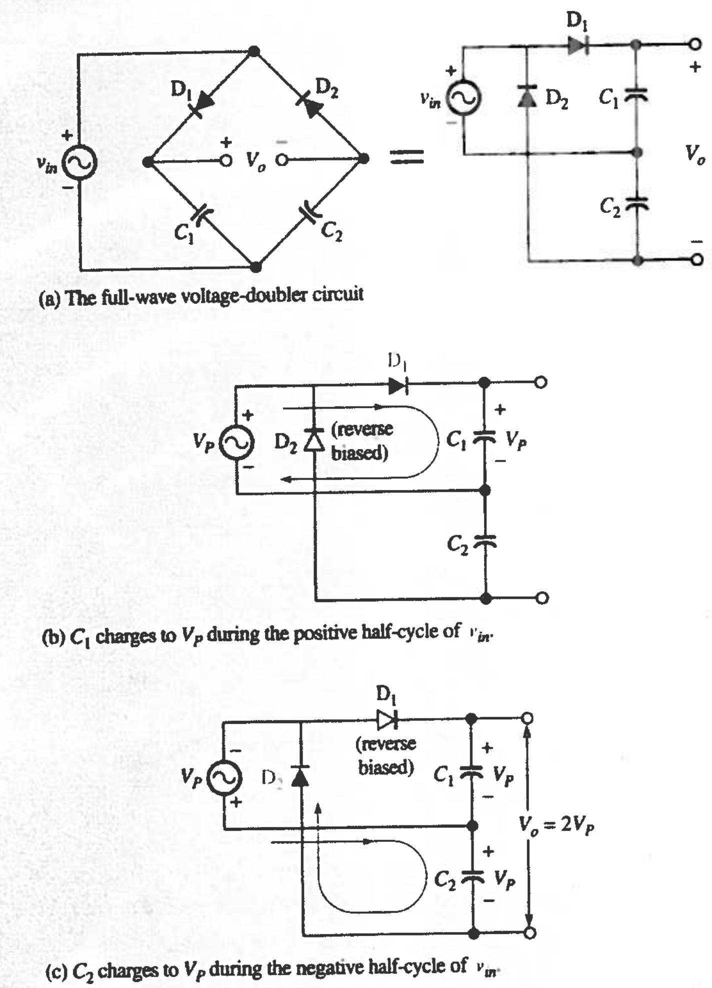


FIGURE 3–26 A full-wave voltage doubler

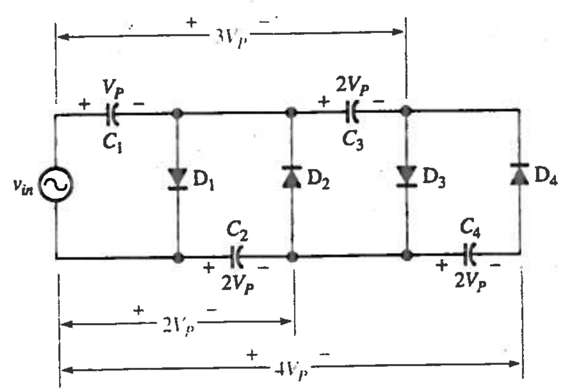


FIGURE 3–27 Voltage tripler and quadrupler

Additional stages can be added in an obvious way to obtain even greater multiples of V_P. The PIV rating of each diode in the circuit must be at least $2V_P$ volts.

3–6 ELEMENTARY VOLTAGE REGULATION

A basic power supply consisting of a transformer, one or more diodes, and a capacitor filter is subject to output voltage variations caused by changes in the load current and the ac line voltage to which the primary of the transformer is connected. If the dc voltage provided by the power supply needs to be constant regardless of the changes just mentioned, some form of voltage regulation must be employed. A simple form of voltage regulation can be obtained by using a *zener* diode, mentioned in Chapter 2, or by employing a three-terminal integrated-circuit (IC) voltage regulator with fixed or adjustable voltage. More advanced power supplies and voltage regulators will be presented later in this text where additional electrical parameters and temperature effects will also be addressed.

The Zener-Diode Voltage Regulator

Zener diodes are specifically designed for operating in their reverse-bias region and are fabricated with a specific zener (avalanche) voltage and power rating. Their forward-bias behavior is no different from common diodes.

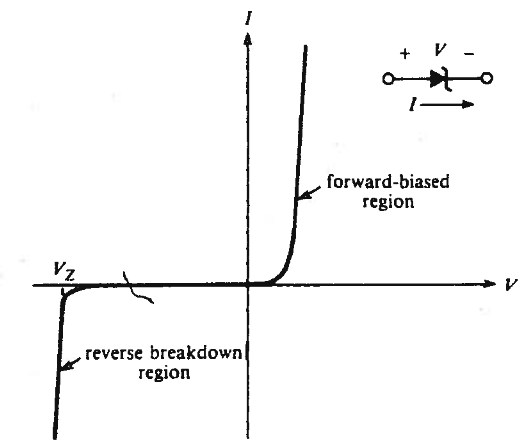


FIGURE 3–28 I–V characteristic of a zener diode

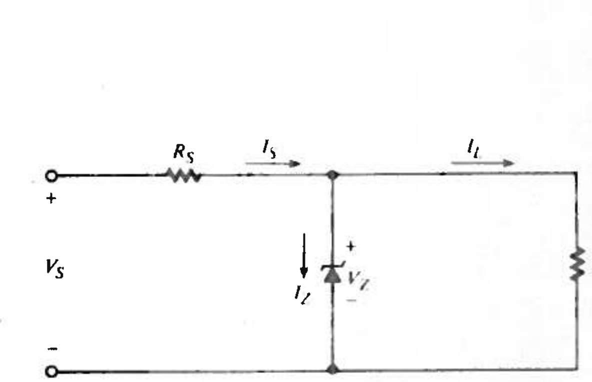


FIGURE 3–29 A simple voltage regulator using a zener diode

Figure 3–28 shows a typical *I–V* characteristic for a zener diode. The forward-biased characteristic is identical to that of a forward-biased silicon diode and obeys the same diode equation that we developed in Chapter 2 (equation 2–2). The zener diode is normally operated in its reverse-biased breakdown region, where the voltage across the device remains substantially constant as the reverse current varies over a large range. Like a fixed voltage source, this ability to maintain a constant voltage across its terminals, independent of current, is what makes the device useful as a voltage reference. The fixed breakdown voltage is called the *zener voltage*, V_Z, as illustrated in the figure.

To demonstrate how a zener diode can serve as a constant voltage reference, Figure 3–29 shows a simple but widely used configuration that maintains a constant voltage across a load resistor. Notice the orientation of V_Z and I_Z. The circuit is an elementary *voltage regulator* that holds the load voltage near V_Z volts as R_L and/or V_S undergo changes. So the voltage across the parallel combination of the zener and R_L remains at V_Z volts, the reverse current I_Z through the diode must at all times be large enough to keep the device in its breakdown region, as shown in Figure 3–28. The value selected for R_S is critical in that respect. As we shall presently demonstrate, R_S must be small enough to permit adequate zener current, yet large enough to prevent the zener current and power dissipation from exceeding permissible limits.

A couple of rules regarding the operation of the zener diode in Figure 3–29 should be addressed at this point:

- The zener current changes in direct proportion to input voltage variations.
- The zener current changes in inverse proportion to load current variations.

This is because the zener diode adjusts its current in order to increase or decrease the voltage drop across R_S and hence maintain a constant voltage V_Z. If V_S increases, I_Z increases, and vice versa; if I_L increases, I_Z decreases, and vice versa.

It is apparent in Figure 3–29 that

$$I_S = I_Z + I_L \tag{3–19}$$

Also, I_S is the voltage difference across R_S divided by R_S:

$$I_S = \frac{V_S - V_Z}{R_S} \tag{3–20}$$

The power dissipated in the zener diode is

$$P_Z = V_Z I_Z \tag{3-21}$$

Solving equation 3–20 for R_S, we find

$$R_S = \frac{V_S - V_Z}{I_S} \tag{3-22}$$

Substituting (3–19) into (3–22) gives

$$R_S = \frac{V_S - V_Z}{I_Z + I_L} \tag{3-23}$$

Let $I_Z(\text{min})$ denote the minimum zener current necessary to ensure that the diode is in its breakdown region. As mentioned earlier, R_S must be small enough to ensure that the $I_Z(\text{min})$ flows under worst-case conditions, namely, when V_S falls to its smallest possible value, $V_S(\text{min})$, and I_L reaches its largest possible value, $I_L(\text{max})$. Thus, from (3–23), we require

$$R_S = \frac{V_S(\text{min}) - V_Z}{I_Z(\text{min}) + I_L(\text{max})} \tag{3-24}$$

With the established value for R_S, we can now determine the actual power dissipation for the resistor and the zener diode. Obviously, maximum power will be dissipated by the resistor when the input voltage is maximum; that is,

$$P_{R_S}(\text{max}) = (V_S(\text{max}) - V_Z)^2/R_S \tag{3-25}$$

Because the zener voltage is constant, maximum power will be dissipated by the zener diode when I_Z is maximum. This happens when V_S is maximum and I_L is minimum according to the preceding rules. Therefore,

$$I_Z(\text{max}) = \frac{V_S(\text{max}) - V_Z}{R_S} - I_L(\text{min}) \tag{3-26}$$

and

$$P_Z(\text{max}) = V_Z I_Z(\text{max}) \tag{3-27}$$

Note that the power rating for R_S should be three or four times the actual maximum power dissipated by R_S. However, such a large safety factor is not necessary for the zener diode. A 50% safety margin is very adequate in this case. For example, if the maximum dissipated power in a zener diode is, say, 600 milliwatts, a 1-watt zener diode will do the job.

Regarding the minimum zener current necessary to keep the diode in its avalanche region (i.e., maintaining regulation), a good rule of thumb is to use 5% to 10% of the maximum load current but no less than a few milliamps in the case of small load currents. For instance, if the maximum load current is 150 mA, the minimum zener current can be set at about 10 mA or so. But if it is only about 10 mA, then the minimum zener current should probably not be set at about 1 mA but more like 3 or 4 mA. It is important to note that, as far as zener dissipation is concerned, the worst-case load condition in some applications may correspond to an open output; that is, $R_L = \infty$ and $I_L = 0$. In that case, all of the current through R_S flows in the zener.

EXAMPLE 3–8

In the circuit of Figure 3–29, $R_S = 20\ \Omega$, $V_Z = 18$ V, and $R_L = 200\ \Omega$. If V_S can vary from 20 V to 30 V, find

1. the minimum and maximum currents in the zener diode;
2. the minimum and maximum power dissipated in the diode; and
3. the rated power dissipation that R_S should have.

Solution

1. Assuming that the zener diode remains in breakdown, then the load voltage remains constant at $V_Z = 18$ V, and the load current therefore remains constant at

$$I_L = \frac{V_Z}{R_L} = \frac{18\text{ V}}{200\ \Omega} = 90\text{ mA}$$

From equation 3–20, when $V_S = 20$ V,

$$I_S = \frac{(20\text{ V}) - (18\text{ V})}{20\ \Omega} = 100\text{ mA}$$

Therefore, $I_Z = I_S - I_L = (100\text{ mA}) - (90\text{ mA}) = 10$ mA. When $V_S = 30$ V,

$$I_S = \frac{(30\text{ V}) - (18\text{ V})}{20\ \Omega} = 600\text{ mA}$$

and $I_Z = I_S - I_L = (600\text{ mA}) - (90\text{ mA}) = 510$ mA.

2. $P_Z(\text{min}) = V_Z I_Z(\text{min}) = (18\text{ V})(10\text{ mA}) = 180$ mW
   $P_Z(\text{max}) = V_Z I_Z(\text{max}) = (18\text{ V})(510\text{ mA}) = 9.18$ W
3. $P_{R_S}(\text{max}) = I_S^2(\text{max})R_S = (0.6)^2(20) = 7.2$ W (rated power should be 20 W)

EXAMPLE 3–9

The current in a certain 10-V, 2-W zener diode must be at least 5 mA to ensure that the diode remains in breakdown. The diode is to be used in the regulator circuit shown in Figure 3–30, where V_S can vary from 15 V to 20 V. Note that the load can be switched out of the regulator circuit in this application. Find a value for R_S. What power dissipation rating should R_S have?

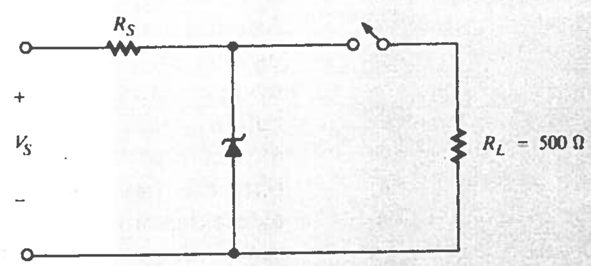
Solution

$V_S(\text{min}) = 15$ V
$I_Z(\text{min}) = 5$ mA
$R_L(\text{min}) = R_L = 500\ \Omega$ (when the switch is closed)

Therefore, from equation 3–24,

$$R_S = \frac{V_S(\text{min}) - V_Z}{I_Z(\text{min}) + V_Z/R_L(\text{min})} = \frac{(15 - 10)\text{ V}}{(5\text{ mA}) + (10\text{ V})/(500\ \Omega)} = 200\ \Omega$$

FIGURE 3–30 (Example 3–9)



$$P_{R_S} = \frac{(20-10)^2}{200} = 0.5 \text{ W (use 2-watt rating)}$$

$$V_S(\max) = 20 \text{ V}, \; I_L(\min) = 0 \text{ (switch open)}$$

$$I_Z(\max) = \frac{V_S(\max) - V_Z}{R_S} - I_L(\min) = \frac{20-10}{200} - 0 = 50 \text{ mA}$$

$$P_Z(\max) = (10 \text{ V})(50 \text{ mA}) = 0.5 \text{ W}$$

The zener diode is operating well under its power rating.

EXAMPLE 3–10

DESIGN

An unregulated dc power supply provides a dc voltage that can vary between 18 and 22 V. Design a 15-volt zener voltage regulator for a load having I_L (min) = 20 mA and I_L (max) = 120 mA. Specify resistor and zener diode values, including power ratings.

Solution

First, the resistor value is calculated based on worst-case conditions for the minimum zener current. Minimum zener current occurs when V_S is minimum and I_L is maximum. Using equation 3–24 with I_Z (min) = 5% of I_L (max), we obtain

$$R_S = \frac{V_S(\min) - V_Z}{I_L(\max) + I_Z(\min)} = \frac{18-15}{120+6} = 23.8\ \Omega \text{ (use 24 ohms)}$$

From equation 3–25,

$$P_{R_S}(\max) = \frac{(22-15)^2}{24} = 2.04 \text{ W (use rating of 5 or 7 watts)}$$

From equation 3–26,

$$I_Z(\max) = \frac{22-15}{24} - .02 \text{ A} = 272 \text{ mA}$$

$$P_Z(\max) = (15 \text{ V})(272 \text{ mA}) = 4.08 \text{ W (use a 5-watt zener diode)}$$

Temperature Effects

The breakdown voltage of a zener diode is a function of the width of its depletion region, which is controlled during manufacturing by the degree of impurity doping. Recall that heavy doping increases conductivity, which narrows the depletion region and therefore decreases the voltage at which breakdown occurs. Zener diodes are available with breakdown voltages ranging from 2.4 V to 200 V. As noted in Chapter 2, the mechanism by which breakdown occurs depends on the breakdown voltage itself. When V_Z is less than about 5 V, the high electric field intensity across the narrow depletion region (around 3×10^7 V/m) strips carriers directly from their bonds, a phenomenon usually called *zener breakdown*. For V_Z greater than about 8 V, breakdown occurs as a result of collisions between high-energy carriers, the mechanism called *avalanching*. Between 5 V and 8 V, both the avalanching and zener mechanisms contribute to breakdown. The practical significance of these facts is that the breakdown mechanism determines how temperature variations affect the value of V_Z. Low-voltage zener diodes that break down by the zener mechanism have negative temperature coefficients (V_Z decreases with increasing temperature) and higher-voltage avalanche zeners have positive temperature coefficients. When V_Z is between about 3 V and 8 V, the temperature coefficient is also strongly influenced by the current in the diode: The coefficient may be positive or negative, depending on current, becoming more positive as current increases.

The temperature coefficient of a zener diode is defined to be its change in breakdown voltage per degree Celsius increase in temperature. For example, a temperature coefficient of +8 mV/°C means that V_Z will increase 8 mV for each degree Celsius increase in temperature. *Temperature stability* is the ratio of the temperature coefficient to the breakdown voltage. Expressed as a percent,

$$S(\%) = \frac{\text{T.C.}}{V_Z} \times 100\% \qquad (3\text{–}28)$$

where T.C. is the temperature coefficient. Clearly, small values of S are desirable.

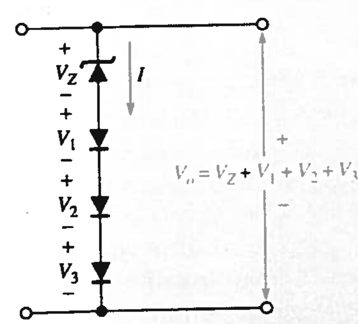
In applications requiring a zener diode to serve as a highly stable voltage reference, steps must be taken to *temperature compensate* the diode. A technique that is used frequently is to connect the zener in series with one or more semiconductor devices whose voltage drops change with temperature in the opposite way that V_Z changes, i.e., devices having the opposite kind of temperature coefficient. If a temperature change causes V_Z to increase, then the voltage across the other components decreases, so the total voltage across the series combination is (ideally) unchanged. For example, the temperature coefficient of a forward-biased silicon diode is negative, so one or more of these can be connected in series with a zener diode having a positive temperature coefficient, as illustrated in Figure 3-31. The next example illustrates that several forward-biased diodes having relatively small temperature coefficients may be required to compensate a single zener diode.

EXAMPLE 3–11

A zener diode having a breakdown voltage of 10 V at 25°C has a temperature coefficient of +5.5 mV/°C. It is to be temperature compensated by connecting it in series with three forward-biased diodes, as shown in Figure 3–31. Each compensating diode has a forward drop of 0.65 V at 25°C and a temperature coefficient of −2 mV/°C.

1. What is the temperature stability of the uncompensated zener diode?
2. What is the breakdown voltage of the uncompensated zener diode at 100°C?
3. What is the voltage across the compensated network at 25°C? At 100°C?

FIGURE 3–31 Temperature compensating a zener diode by connecting it in series with forward-biased diodes having opposite temperature coefficients



4. What is the temperature stability of the compensated network?

Solution

1. From equation 3–27,

$$S = \frac{\text{T.C.} \times 100\%}{V_Z} = \frac{5.5 \times 10^{-3}}{10\ \text{V}} \times 100\% = 0.055\%$$

2. $V_Z = (10\,\text{V}) + \Delta T(\text{T.C.}) = (10\,\text{V}) + (100°\text{C} - 25°\text{C})(5.5\ \text{mV/°C}) = 10.4125\,\text{V}$
3. As shown in Figure 3–31, $V_o = V_Z + V_1 + V_2 + V_3$. At 25°C, $V_o = 10 + 3(0.65) = 11.95$ V. At 100°C, the drop V_D across each forward-biased diode is $V_D = (0.65\,\text{V}) + (100°\text{C} - 25°\text{C})(-2\ \text{mV/°C}) = 0.5$ V. Therefore, at 100°C, $V_o = (10.4125\,\text{V}) + 3(0.5\,\text{V}) = 10.5625$ V.
4. The temperature coefficient of the compensated network is T.C. = $(+5.5\ \text{mV/°C}) + 3(-2\ \text{mV/°C}) = (+5.5\ \text{mV/°C}) - (6\ \text{mV/°C}) = -0.5$ mV/°C. The voltage drop across the network (at 25°C) was found to be 11.95 V, so

$$S = \frac{-0.5\ \text{mV/°C}}{11.95} \times 100\% = -0.00418\%$$

We see that compensation has improved the stability by a factor greater than 10.

Temperature-compensated zener diodes are available from manufacturers in single-package units called *reference diodes.* These units contain specially fabricated junctions that closely track and oppose variations in V_Z with temperature. Although it is possible to obtain an extremely stable reference this way, it may be necessary to maintain the zener current at a manufacturer's specified value in order to realize the specified stability.

Zener-Diode Impedance

The breakdown characteristic of an *ideal* zener diode is a perfectly vertical line, signifying zero change in voltage for any change in current. Thus, the ideal diode has zero impedance (or ac resistance) in its breakdown region. A practical zener diode has nonzero impedance, which can be computed in the usual way:

$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z} \tag{3–29}$$

Z_Z is the reciprocal of the slope of the breakdown characteristic on an I_Z-V_Z plot. The slope is not constant, so the value of Z_Z depends on the point along the characteristic where the measurement is made. The impedance decreases as I_Z increases; that is, the breakdown characteristic becomes steeper at points farther down the line, corresponding to greater reverse currents. For this reason, the diode should be operated with as much reverse current as possible, consistent with rating limitations.

Manufactures' specifications for zener impedances are usually given for a specified ΔI_Z that covers a range from a small I_Z near the onset of breakdown to some percentage of the maximum rated I_Z. The values may range from a few ohms to several hundred ohms. There is also a variation in the impedance of zener diodes among those having different values of V_Z. Diodes with breakdown voltages near 7 V have the smallest impedances.

EXAMPLE 3-12

A zener diode has impedance 40 Ω in the range from $I_Z = 1$ mA to $I_Z = 10$ mA. The voltage at $I_Z = 1$ mA is 9.1 V. Assuming that the impedance is constant over the given range, what minimum and maximum zener voltages can be expected if the diode is used in an application where the zener current changes from 2 mA to 8 mA?

Solution

From equation 3–29, the voltage change between $I_Z = 1$ mA and $I_Z = 2$ mA is $\Delta V_Z = \Delta I_Z Z_Z = [(2\ \text{mA}) - (1\ \text{mA})](40\ \Omega) = 0.04$ V. Therefore, the minimum voltage is $V_Z(\text{min}) = (9.1\,\text{V}) + \Delta V_Z = (9.1\,\text{V}) + (0.04\,\text{V}) = 9.14$ V. The voltage change between $I_Z = 2$ mA and $I_Z = 8$ mA is $\Delta V_Z = [(8\ \text{mA}) - (2\ \text{mA})](40\ \Omega) = 0.16$ V. Therefore, the maximum voltage is $V_Z(\text{max}) = V_Z(\text{min}) + \Delta V_Z = (9.14\ \text{V}) + (0.16\,\text{V}) = 9.3$ V.

Three-Terminal Integrated-Circuit Regulators

A three-terminal regulator is a compact, easy-to-use, fixed-voltage regulator packaged in a single integrated circuit. To use the regulator, it is necessary only to make external connections to the three terminals: V_{in}, V_o, and ground. These devices are widely used to provide *local regulation* in electronic systems that may require several different supply voltages. For example, a 5-V regulator could be used to regulate the power supplied to all the chips mounted on one printed circuit board, and a 12-V regulator could be used for a similar purpose on a different board. The regulators might well use the same unregulated input voltage, say, 20 V.

A popular series of three-terminal regulators is the 7800/7900 series, available from several manufacturers with a variety of output voltage ratings. Figure 3–32 shows National Semiconductor specifications for their 7800-series regulators, which carry the company's standard LM prefix and which are available with regulated outputs of +5 V, +12 V, and +15 V. The last two digits of the 7800 number designate the rated output voltage. For example, the 7805 is a +5-V regulator and the 7815 is a +15-V regulator. The 7900-series regulators provide negative output voltages. Notice that the integrated circuitry shown in the schematic diagram is considerably complex. It can be seen that the circuit incorporates a zener diode as an internal voltage reference. The 7800/7900 series also has internal current-limiting circuitry.

Important points to note in the 7800-series specifications include the following:

1. The output voltage of an arbitrarily chosen device might not *exactly* equal its nominal value. For example, with a 23-V input, the 7815 output may be anywhere from 14.4 V to 15.6 V. This specification does not mean that the output voltage of a single device will vary over that range, but that one 7815 chosen at random from a large number will hold its output constant at some voltage within that range.
2. The input voltage cannot exceed 35 V and must not fall below a certain minimum value, depending on type number, if output regulation is to be maintained. The minimum specified inputs are 7.3, 14.6, and 17.7 V for the 7805, 7812, and 7815, respectively.
3. Load regulation is specified as a certain output voltage change (ΔV_o) as the load current (I_o) is changed over a certain range. For example, the output of the 7805 will change a maximum of 50 mV as load current changes from 5 mA to 1.5 A, and will change a maximum of 25 mV as load current changes from 250 mA to 750 mA.

National Semiconductor

Voltage Regulators

LM78XX Series

LM78XX Series Voltage Regulators

General Description

The LM78XX series of three terminal regulators is available with several fixed output voltages making them useful in a wide range of applications. One of these is local on card regulation, eliminating the distribution problems associated with single point regulation. The voltages available allow these regulators to be used in logic systems, instrumentation, HiFi, and other solid state electronic equipment. Although designed primarily as fixed voltage regulators these devices can be used with external components to obtain adjustable voltages and currents.

The LM78XX series is available in an aluminum TO-3 package which will allow over 1.0A load current if adequate heat sinking is provided. Current limiting is included to limit the peak output current to a safe value. Safe area protection for the output transistor is provided to limit internal power dissipation. If internal power dissipation becomes too high for the heat sinking provided, the thermal shutdown circuit takes over preventing the IC from overheating.

Considerable effort was expended to make the LM78XX series of regulators easy to use and minimize the number of external components. It is not necessary to bypass the output, although this does improve transient response. Input bypassing is needed only if the regulator is located far from the filter capacitor of the power supply.

For output voltage other than 5V, 12V and 15V the LM117 series provides an output voltage range from 1.2V to 57V.

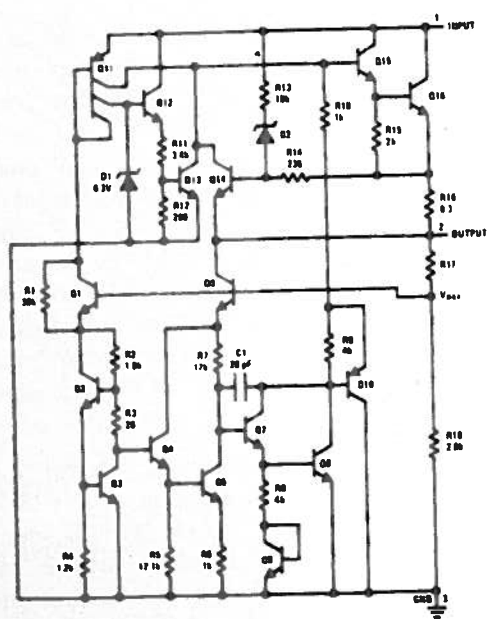
Features

- Output current in excess of 1A
- Internal thermal overload protection
- No external components required
- Output transistor safe area protection
- Internal short circuit current limit
- Available in the aluminum TO-3 package

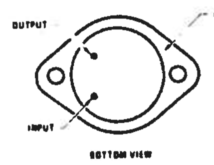
Voltage Range

LM7805C 5V
LM7812C 12V
LM7815C 15V

Schematic and Connection Diagrams

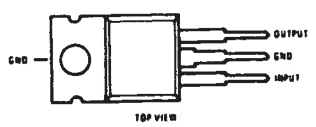


Metal Can Package
TO-3 (K)
Aluminum



Order Numbers
LM7805CK
LM7812CK
LM7815CK
See Package KC02A

Plastic Package
TO-220 (T)



Order Numbers:
LM7805CT
LM7812CT
LM7815CT
See Package T03B

FIGURE 3–32 7800-series voltage-regulator specifications (Courtesy of National Semiconductor)

For negative voltage regulation, the 7900 series provides the same characteristics as the 7800 series but for negative input and output voltage.

Another popular three-terminal IC regulator is the LM317, which can provide adjustable output voltage by simply adding a few external components. The LM317 can supply up to 1.5 A of current to a load when mounted

LM78XX Series

Absolute Maximum Ratings

Input Voltage (V_O = 5V, 12V and 15V)	35V
Internal Power Dissipation (Note 1)	Internally Limited
Operating Temperature Range (T_A)	0 °C to +70 °C
Maximum Junction Temperature	
(K Package)	150 °C
(T Package)	125 °C
Storage Temperature Range	−65 °C to +150 °C
Lead Temperature (Soldering, 10 seconds)	
TO-3 Package K	300 °C
TO-220 Package T	230 °C

Electrical Characteristics LM78XXC (Note 2) 0 °C ≤ Tj ≤ 125 °C unless otherwise noted

OUTPUT VOLTAGE			5V			12V			15V			UNITS
INPUT VOLTAGE (unless otherwise noted)			10V			19V			23V			
PARAMETER	CONDITIONS		MIN	TYP	MAX	MIN	TYP	MAX	MIN	TYP	MAX	
V_O Output Voltage	T_j = 25 °C, 5 mA ≤ I_O ≤ 1A		4.8	5	5.2	11.5	12	12.5	14.4	15	15.6	V
	P_D ≤ 15W, 5 mA ≤ I_O ≤ 1A		4.75		5.25	11.4		12.6	14.25		15.75	V
	V_{MIN} ≤ V_{IN} ≤ V_{MAX}		(7 ≤ V_{IN} ≤ 20)			(14.5 ≤ V_{IN} ≤ 27)			(17.5 ≤ V_{IN} ≤ 30)			V
ΔV_O Line Regulation	I_O = 500 mA	T_j = 25 °C ΔV_{IN}		3	50		4	120		4	150	mV
			(7 ≤ V_{IN} ≤ 25)			(14.5 ≤ V_{IN} ≤ 30)			(17.5 ≤ V_{IN} ≤ 30)			V
		0 °C ≤ T_j ≤ +125 °C ΔV_{IN}			50			120			150	mV
			(8 ≤ V_{IN} ≤ 20)			(15 ≤ V_{IN} ≤ 27)			(18.5 ≤ V_{IN} ≤ 30)			V
	I_O ≤ 1A	T_j = 25 °C ΔV_{IN}			50			120			150	mV
			(7.3 ≤ V_{IN} ≤ 20)			(14.6 ≤ V_{IN} ≤ 27)			(17.7 ≤ V_{IN} ≤ 30)			V
		0° ≤ T_j ≤ +125 °C ΔV_{IN}			25			60			75	mV
			(8 ≤ IN ≤ 12)			(16 ≤ V_{IN} ≤ 22)			(20 ≤ V_{IN} ≤ 26)			V
ΔV_O Load Regulation	T_j = 25 °C	5 mA ≤ I_O ≤ 1.5A		10	50		12	120		12	150	mV
		250 mA ≤ I_O ≤ 750 mA			25			60			75	mV
	5 mA ≤ I_O ≤ 1A, 0 °C ≤ T_j ≤ +125 °C				50			120			150	mV
I_Q Quiescent Current	I_O ≤ 1A	T_j = 25 °C			8			8			8	mA
		0 °C ≤ T_j ≤ +125 °C			8.5			8.5			8.5	mA
ΔI_Q Quiescent Current Change	5 mA ≤ I_O ≤ 1A				0.5			0.5			0.5	mA
	T_j = 25 °C, I_O ≤ 1A				1.0			1.0			1.0	mA
	V_{MIN} ≤ V_{IN} ≤ V_{MAX}		(7.5 ≤ V_{IN} ≤ 20)			(14.8 ≤ V_{IN} ≤ 27)			(17.9 ≤ V_{IN} ≤ 30)			V
	I_O ≤ 500 mA, 0 °C ≤ T_j ≤ +125 °C				1.0			1.0			1.0	mA
	V_{MIN} ≤ V_{IN} ≤ V_{MAX}		(7 ≤ V_{IN} ≤ 25)			(14.5 ≤ V_{IN} ≤ 30)			(17.5 ≤ V_{IN} ≤ 30)			V
V_N Output Noise Voltage	T_A = 25 °C, 10 Hz ≤ f ≤ 100 kHz			40			75			90		μV
$\frac{\Delta V_{IN}}{\Delta V_{OUT}}$ Ripple Rejection	f = 120 Hz	I_O ≤ 1A, T_j = 25 °C or	62	80		55	72		54	70		dB
		I_O ≤ 500 mA, 0 °C ≤ T_j ≤ +125 °C	62			55			54			dB
	V_{MIN} ≤ V_{IN} ≤ V_{MAX}		(8 ≤ V_{IN} ≤ 18)			(15 ≤ V_{IN} ≤ 25)			(18.5 ≤ V_{IN} ≤ 28.5)			V
R_O Dropout Voltage	T_j = 25 °C, I_{OUT} = 1A			2.0			2.0			2.0		V
Output Resistance	f = 1 kHz			8			18			19		mΩ
Short-Circuit Current	T_j = 25 °C			2.1			1.5			1.2		A
Peak Output Current	T_j = 25 °C			2.4			2.4			2.4		A
Average TC of V_{OUT}	0 °C ≤ T_j ≤ +125 °C, I_O = 5 mA			0.6			1.5			1.8		mV/°C
V_{IN} Input Voltage Required to Maintain Line Regulation	T_j = 25 °C, I_O ≤ 1A		7.3			14.6			17.7			V

NOTE 1: Thermal resistance of the TO-3 package (K, KC) is typically 4°C/W junction to case and 35°C/W case to ambient. Thermal resistance of the TO-220 package (T) is typically 4°C/W junction to case and 50°C/W case to ambient.

NOTE 2: All characteristics are measured with capacitor across the inut of 0.22 μF, and a capacitor across the output of 0.1 μF. All characteristics except noise voltage and ripple rejection ratio are measured using pulse techniques (t_w ≤ 10 ms, duty cycle ≤ 5%). Output voltage changes due to changes in internal temperature must be taken into account separately.

FIGURE 3–32 Continued

on a suitable heat sink. Figure 3–33 shows the specifications for this regulator. For negative voltage regulation, the LM337 is very much like the mirror image of the LM317 positive regulator.

Both regulators operate based on an internal fixed voltage reference of 1.25 V and a bias current of 100 μA, as shown in Figure 3–34. Resistor R_1 establishes a current of (1.25 V)/R_1, which, together with the bias current I_A, produces a voltage drop across R_2. The output voltage will then be

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National Semiconductor

LM117/LM317A/LM317
3-Terminal Adjustable Regulator

General Description

The LM117 series of adjustable 3-terminal positive voltage regulators is capable of supplying in excess of 1.5A over a 1.2V to 37V output range. They are exceptionally easy to use and require only two external resistors to set the output voltage. Further, both line and load regulation are better than standard fixed regulators. Also, the LM117 is packaged in standard transistor packages which are easily mounted and handled.

In addition to higher performance than fixed regulators, the LM117 series offers full overload protection available only in IC's. Included on the chip are current limit, thermal overload protection and safe area protection. All overload protection circuitry remains fully functional even if the adjustment terminal is disconnected.

Normally, no capacitors are needed unless the device is situated more than 6 inches from the input filter capacitors in which case an input bypass is needed. An optional output capacitor can be added to improve transient response. The adjustment terminal can be bypassed to achieve very high ripple rejection ratios which are difficult to achieve with standard 3-terminal regulators.

Besides replacing fixed regulators, the LM117 is useful in a wide variety of other applications. Since the regulator is "floating" and sees only the input-to-output differential voltage, supplies of several hundred volts can be regulated as long as the maximum input to output differential is not exceeded, i.e., avoid short-circuiting the output.

Also, it makes an especially simple adjustable switching regulator, a programmable output regulator, or by connecting a fixed resistor between the adjustment pin and output, the LM117 can be used as a precision current regulator. Supplies with electronic shutdown can be achieved by clamping the adjustment terminal to ground which programs the output to 1.2V where most loads draw little current.

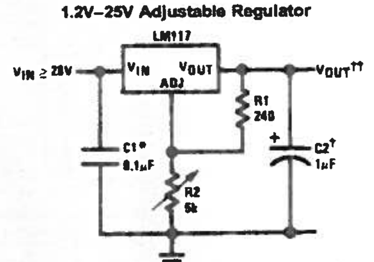
For applications requiring greater output current, see LM150 series (3A) and LM138 series (5A) data sheets. For the negative complement, see LM137 series data sheet.

Features

- Guaranteed 1% output voltage tolerance (LM317A)
- Guaranteed max. 0.01%/V line regulation (LM317A)
- Guaranteed max. 0.3% load regulation (LM117)
- Guaranteed 1.5A output current
- Adjustable output down to 1.2V
- Current limit constant with temperature
- P+ Product Enhancement tested
- 80 dB ripple rejection
- Output is short-circuit protected

Typical Applications

1.2V–25V Adjustable Regulator



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Full output current not available at high input-output voltages

*Needed if device is more than 6 inches from filter capacitors.

†Optional — improves transient response. Output capacitors in the range of 1 μF to 1000 μF of aluminum or tantalum electrolytic are commonly used to provide improved output impedance and rejection of transients.

$$††V_{OUT} = 1.25V\left(1 + \frac{R2}{R1}\right) + I_{ADJ}(R_2)$$

LM117 Series Packages

Part Number Suffix	Package	Design Load Current
K	TO-3	1.5A
H	TO-39	0.5A
T	TO-220	1.5A
E	LCC	0.5A
S	TO-263	1.5A
EMP	SOT-223	1A
MDT	TO-252	0.5A

SOT-223 vs D-Pak (TO-252) Packages

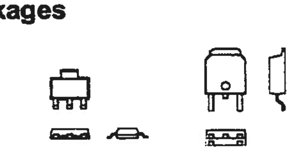

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FIGURE 3–33 Specifications for the LM317/LM117 (Reprinted with permission of National Semiconductor Corporation)

$$V_o = V_{ref} + \left(I_A + \frac{V_{ref}}{R_1}\right)R_2$$

where I_A = 100 μA and V_{ref} = 1.25 V, nominally. The manufacturer recommends 240 ohms for R_1 to establish a current of about 5 mA through it. When this is the case, I_A can be neglected and V_o can be approximated by $V_o = V_{ref}(1 + R_2/R_1)$. The output voltage can be made adjustable by using

Electrical Characteristics (Note 3)

Specifications with standard type face are for T_J = 25°C, and those with **boldface type** apply over **full Operating Temperature Range**. Unless otherwise specified, $V_{IN} - V_{OUT}$ = 5V, and I_{OUT} = 10 mA

Parameter	Conditions	LM317A Min	LM317A Typ	LM317A Max	LM317 Min	LM317 Typ	LM317 Max	Units
Reference Voltage		1.238	1.250	1.262				V
	$3V \leq (V_{IN} - V_{OUT}) \leq 40V$, $10\ mA \leq I_{OUT} \leq I_{MAX}$, $P \leq P_{MAX}$	**1.225**	**1.250**	**1.270**	**1.20**	1.25	**1.30**	V
Line Regulation	$3V \leq (V_{IN} - V_{OUT}) \leq 40V$ (Note 4)		0.005	0.01		0.01	0.04	%/V
			0.01	**0.02**		**0.02**	**0.07**	%/V
Load Regulation	$10\ mA \leq I_{OUT} \leq I_{MAX}$ (Note 4)		0.1	0.5		0.1	0.5	%
			0.3	**1**		**0.3**	**1.5**	%
Thermal Regulation	20 ms Pulse		0.04	0.07		0.04	0.07	%/W
Adjustment Pin Current			**50**	**100**		**50**	**100**	μA
Adjustment Pin Current Change	$10\ mA \leq I_{OUT} \leq I_{MAX}$, $3V \leq (V_{IN} - V_{OUT}) \leq 40V$		**0.2**	**5**		**0.2**	**5**	μA
Temperature Stability	$T_{MIN} \leq T_J \leq T_{MAX}$		**1**			**1**		%
Minimum Load Current	$(V_{IN} - V_{OUT}) = 40V$		**3.5**	**10**		**3.5**	**10**	mA
Current Limit	$(V_{IN} - V_{OUT}) \leq 15V$							
	K, T, S Packages	**1.5**	**2.2**	**3.4**	**1.5**	**2.2**	**3.4**	A
	H Package	**0.5**	**0.8**	**1.8**	**0.5**	**0.8**	**1.8**	A
	MP Package	**1.5**	**2.2**	**3.4**	**1.5**	**2.2**	**3.4**	A
	$(V_{IN} - V_{OUT}) = 40V$							
	K, T, S Packages	0.15	0.4		0.15	0.4		A
	H Package	0.075	0.2		0.075	0.2		A
	MP Package	0.55	0.4		0.15	0.4		A
RMS Output Noise, % of V_{OUT}	10 Hz ≤ f ≤ 10 kHz		0.003			0.003		%
Ripple Rejection Ratio	V_{OUT} = 10V, f = 120 Hz, C_{ADJ} = 0 μF		65			65		dB
	V_{OUT} = 10V, f = 120 Hz, C_{ADJ} = 10 μF	**66**	80		**66**	80		dB
Long-Term Stability	T_J = 125°C, 1000 hrs		0.3	1		0.3	1	%
Thermal Resistance, Junction-to-Case	K Package					2.3	3	°C/W
	MDT Package					5		°C/W
	H Package		12	15		12	15	°C/W
	T Package		4	5		4		°C/W
	MP Package		23.5			23.5		°C/W
Thermal Resistance, Junction-to-Ambient (No Heat Sink)	K Package		35			35		°C/W
	MDT Package(Note 6)					92		°C/W
	H Package		140			140		°C/W
	T Package		50			50		°C/W
	S Package (Note 6)		50			50		°C/W

Note 1: Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is intended to be functional, but do not guarantee specific performance limits. For guaranteed specifications and test conditions, see the Electrical Characteristics. The guaranteed specifications apply only for the test conditions listed.

Note 2: Refer to RETS117H drawing for the LM117H, or the RETS117K for the LM117K military specifications.

Note 3: Although power dissipation is internally limited, these specifications are applicable for maximum power dissipations of 2W for the TO-39 and SOT-223 and 20W for the TO-3, TO-220, and TO-263. I_{MAX} is 1.5A for the TO-3, TO-220, and TO-263 packages, 0.5A for the TO-39 package and 1A for the SOT-223 Package. All limits (i.e., the numbers in the Min. and Max. columns) are guaranteed to National's AOQL (Average Outgoing Quality Level).

Note 4: Regulation is measured at a constant junction temperature, using pulse testing with a low duty cycle. Changes in output voltage due to heating effects are covered under the specifications for thermal regulation.

Note 5: Human body model, 100 pF discharged through a 1.5 kΩ resistor.

Note 6: If the TO-263 or TO-252 packages are used, the thermal resistance can be reduced by increasing the PC board copper area thermally connected to the package. If the SOT-223 package is used, the thermal resistance can be reduced by increasing the PC board copper area (see applications hints for heatsinking).

3 www.national.com

FIGURE 3–33 Continued

a variable resistor for R_2. For better results, 1-μF tantalum capacitors can be connected across both the input and output sides (see data sheet).

3–7 DIODE TYPES, RATINGS, AND SPECIFICATIONS

Discrete diodes—those packaged in individual cases with externally accessible anode and cathode connections—are commercially available in a wide

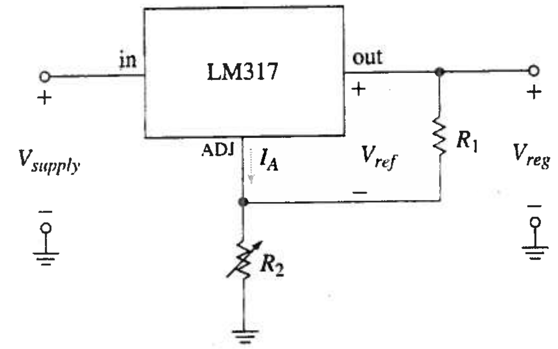


FIGURE 3–34 A very simple adjustable positive voltage regulator with the LM317

range of types designed for different kinds of service and for a variety of applications. We find, for example, *switching* diodes designed specifically for use in logic circuit applications, like those discussed in the last section. These diodes typically have low power-dissipation ratings, are small in size, and are designed to respond rapidly to pulse-type inputs, that is, to switch between their ON and OFF states with minimum delay. *Rectifier* or *power* diodes are designed to carry larger currents and to dissipate more power than switching diodes. They are used in power supply applications, where heavier currents and higher voltages are encountered. *Small-signal* diodes are general-purpose diodes used in applications such as signal detection in radio and TV.

Figure 3–35 illustrates the variety of sizes and shapes that commercially available diodes may have. Each of those shown has a designation that identifies the standard case size it has (DO-4, DO-7, etc.). Materials used for case construction include glass, plastic, and metal. Metal cases are used for large, rectifier-type diodes to enhance the conduction of heat and improve their power-dissipation capabilities.

There are two particularly important diode ratings that a designer using commercial, discrete diodes should know when selecting a diode for any application: the *maximum reverse voltage* (V_{RM}) and the *maximum forward current*. The maximum reverse voltage, also called the *peak inverse voltage* (PIV), is the maximum reverse-biasing voltage that the diode can withstand without breakdown. If the PIV is exceeded, the diode "breaks down" only in the sense that it readily conducts current in the reverse direction. As discussed in Chapter 2, breakdown *may* result in permanent failure if the power dissipation rating of the device is exceeded. The maximum forward current is the maximum current that the diode can sustain when it is forward biased. Exceeding this rating will cause excessive heat to be generated in the diode and will lead to permanent failure. Manufacturers' ratings for the maximum forward current will specify whether the rating is for continuous, peak, average, or rms current, and they may provide different values for each. The symbols I_o and I_F are used to represent forward current.

EXAMPLE 3–13

DESIGN

In the circuit of Figure 3–36, a rectifier diode is used to supply positive current pulses to the 100-Ω resistor load. The diode is available in the combinations of ratings listed in the table portion of the figure. Which is the least expensive diode that can be used for the application?

Solution

The applied voltage is 120 V rms. Therefore, when the diode is reverse biased by the *peak* negative value of the sine wave, it will be subjected to a maximum

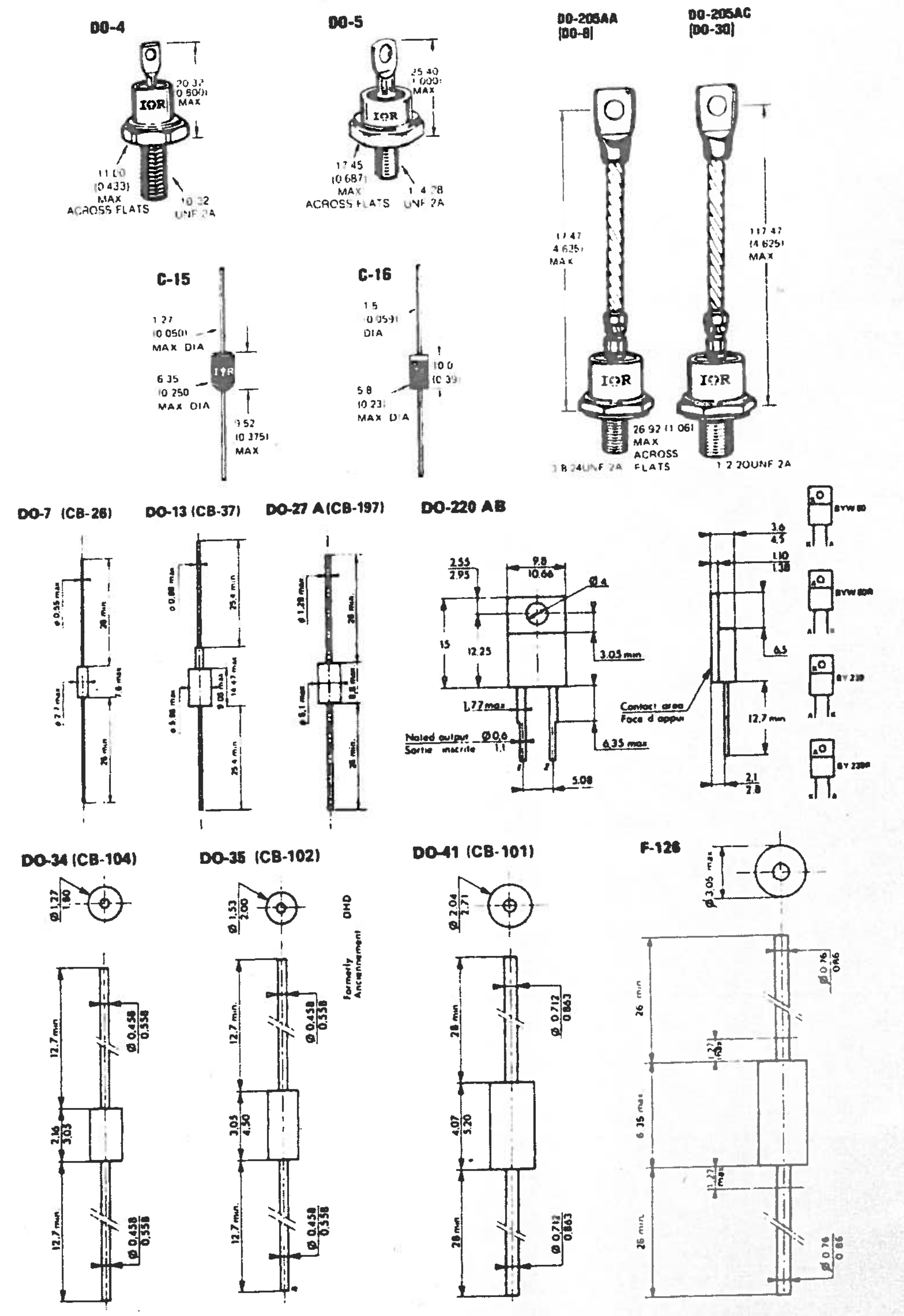


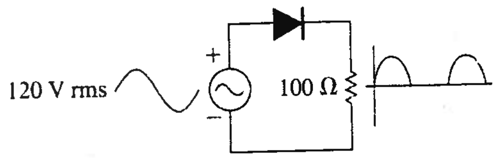
FIGURE 3–35 Discrete diode case styles (Courtesy of International Rectifier Corp. and Thomson-CSF Components Corp.)

reverse-biasing voltage of (1.414)(120) = 169.7 V. The V_{RM} rating must be greater than 169.7 V.

The average value of the current is one-half the average value of a single sinusoidal pulse: $I_{AVG} = (1/2)(0.637\ I_P)$ A, where I_P is the peak value of the pulse. (Note that the factor 1/2 must be used because the pulse is present for only one-half of each full cycle.) The peak forward current in the example (neglecting the

FIGURE 3–36
(Example 3–13)

V_{RM}	Max I_o (average)	Unit Cost
100 V	1.0 A	\$0.50
150 V	2.0 A	1.50
200 V	1.0 A	2.00
200 V	2.0 A	3.00
500 V	2.0 A	3.50
500 V	5.0 A	5.00



drop across the diode) is $I_P = (169.7\,\text{V})/(100\,\Omega) = 1.697$ A. Therefore, the average forward current through the diode is $I_{AVG} = (1/2)(0.637 + 1.697) = 0.540$ A.

The least expensive diode having ratings adequate for the peak inverse voltage and average forward current values we calculated is the one costing \$2.00.

Figure 3–37 shows a typical manufacturer's specification sheet for a line of silicon small-signal diodes. Like many other manufactured electronic components, diodes are often identified by a standard *type* number in accordance with JEDEC (Joint Electron Devices Engineering Council) specifications. Diode-type numbers have the prefix 1N, like those shown in the leftmost column of Figure 3–37. (Not all manufacturers provide JEDEC numbers; many use their own commercial part numbers.) The second column in the specification sheet shows the maximum reverse voltage, V_{RM}, for each of the diode types. Note that V_{RM} ranges from 20 V to 200 V for the diodes listed. The third column shows the rated average forward current, I_o, of each diode in mA, and these range from 0.1 mA to 200 mA. The next two pairs of columns list values of reverse current, I_R, for different values of reverse voltage, V_R, and ambient temperature, T_{amb}. The next column gives capacitance values in pF, an important specification in high-frequency and switching applications. The column headed t_{rr} lists the reverse recovery time of each diode, in nanoseconds. This specification relates to the time required for a diode to switch from its ON to its OFF state and is another important parameter in switching circuit design. Finally, the maximum rated power dissipation is given in mW. The product of diode voltage and diode current should never exceed this rating in any application (unless there is some auxiliary means for removing heat, such as a cooling fan).

Figure 3–38(a) shows a typical specification sheet for a line of silicon rectifier diodes. Note that the forward current ratings for these diodes are generally larger than those of the small-signal diodes. The current ratings are given as $I_{F(AV)}$ (average), and I_{FSM}, each in units of amperes. I_{FSM} is the maximum nonrepetitive forward current that the diode can sustain, that is, the maximum value of momentary or *surge* current it can conduct. Note that the I_{FSM} values are much larger than the $I_{F(AV)}$ values. The voltage ratings are specified by V_{RPM}, the maximum repetitive reverse voltage that each diode can sustain. Also note the large physical sizes and the metal cases of the stud-mounted rectifiers that are capable of conducting currents from 12 to 40 A.

Diode bridges are commonly available in single-package units. These packages have a pair of terminals to which the ac input is connected and

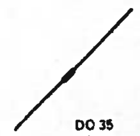
THOMSON-CSF

silicon signal diodes

T_{amb} = 25°C

GENERAL PURPOSE AND HIGH SPEED SWITCHING

Type	V_R-V_{RM} max (V)	I_O V_F = 1V min (mA)	I_R (μA)	/ V_R (V)	I_R (μA)	/ T_{amb} (°C)	C max (pF)	t_{rr} (ns)	P_{tot} (mW)	Case
1N 456	30	40	0,025	25	5	150			250	
1N 456A	30	100	0,025	25	5	150			250	
1N 457	70	20	0,025	60	5	150			250	
1N 457A	70	100	0,025	60	5	150			250	
1N 458	150	7	0,025	125	5	150			250	
1N 458A	150	100	0,025	125	5	150			250	
1N 461	30	15	0,5	25	30	150			250	
1N 461A	30	100	0,5	25	30	150			250	
1N 462	70	5	0,5	60	30	150			250	
1N 462A	70	100	0,5	60	30	150			250	
1N 463	200	1	0,5	175	30	150			250	
1N 464	150	3	0,5	125	30	150			250	
1N 464A	150	100	0,5	125	30	150			250	
1N 482	40	100 *	0,25	30	30	150			250	
1N 482A	40	100	0,025	30	15	150			250	
1N 482B	40	100	0,025	30	5	150			250	
1N 483	70	100 *	0,25	60	30	150			250	
1N 484	130	100 *	0,25	125	30	150			250	
1N 484A	130	100	0,025	125	15	150			250	
1N 484B	130	100	0,025	125	5	150			250	
1N 914	100	10	0,025	20	50	150	4	4	250	
1N 914A	100	20	0,025	20	50	150	4	4	250	
1N 914B	100	100	0,025	20	50	150	4	4	250	
1N 916	100	10	0,025	20	50	150	2	4	250	
1N 916A	100	20	0,025	20	50	150	2	4	250	
1N 916B	100	30	0,025	20	50	150	2	4	250	
1N 3062	75	20	0,1	50	100	150	1	2	250	
1N 3063	75	10	0,1	50	100	150	2	4	250	
1N 3064	75	10	0,1	50	100	150	2	4	250	
1N 3066	75	50	0,1	50	100	150	6	50	250	
1N 3070	200	100	0,1	150	100	150	5	50	250	
1N 3071	200	200	0,1	125	500	125	8	3000	500	
1N 3595	150	200	0,1	50	100	150	2.5	4	250	
1N 3600	50	10	0,1	50	100	150	1	2	250	
1N 3604		50	0,05	50	50	150	2	2	250	
1N 3605		0,1**	0,05	30	50	150	2	2	250	
1N 3606		0,1**	0,05	50	50	150	2	2	250	
1N 4148	100	10	0,025	20	50	150	4	4	500	
1N 4149	100	10	0,025	20	50	150	2	4	500	
1N 4150	50	200	0,1	50	100	150	2.5	4	500	
1N 4151	75	50	0,05	50	50	150	2	2	500	
1N 4152	40	0,1**	0,05	30	50	150	2	2	500	
1N 4153	75	0,1**	0,05	50	50	150	2	2	500	
1N 4154	25	30	0,1	25	100	150	4	2	500	
1N 4244	20	20	0,1	10	100	150	0.8	0.75	250	
1N 4305	75	10	0,1	50	100	150	2	4	500	
1N 4446	100	20	0,025	20	50	150	4	4	500	
1N 4447	100	20	0,025	20	50	150	2	4	500	
1N 4448	100	100	0,025	20	50	150	4	4	500	
1N 4449	100	30	0,025	20	50	150	2	4	500	
1N 4450	40	200	0,05	30	50	150	4	4	500	
1N 4454	75	10	1	50	100	150	2	4	500	



*V_F = 1,1V **V_F = 0,55V

FIGURE 3–37 A typical diode data sheet (Courtesy of Thomson-CSF)

another pair at which the full-wave–rectified output is taken. Figure 3-38(b) shows a typical manufacturer's specification sheet for a line of single-package bridges with current ratings from 1 to 100 A. The V_{RRM} specifications refer to the maximum repetitive reverse voltage ratings of each, i.e., the peak inverse voltage ratings when operated with repetitive inputs, such as sinusoidal voltages. These ratings range from 50 to 1200 V. Note the I_{FSM} specifications, which refer to maximum forward surge current.

Power Supply Component Specifications

Designing a simple power supply, as the reader might have already concluded, should not be a lengthy and difficult task. Nevertheless, the designer

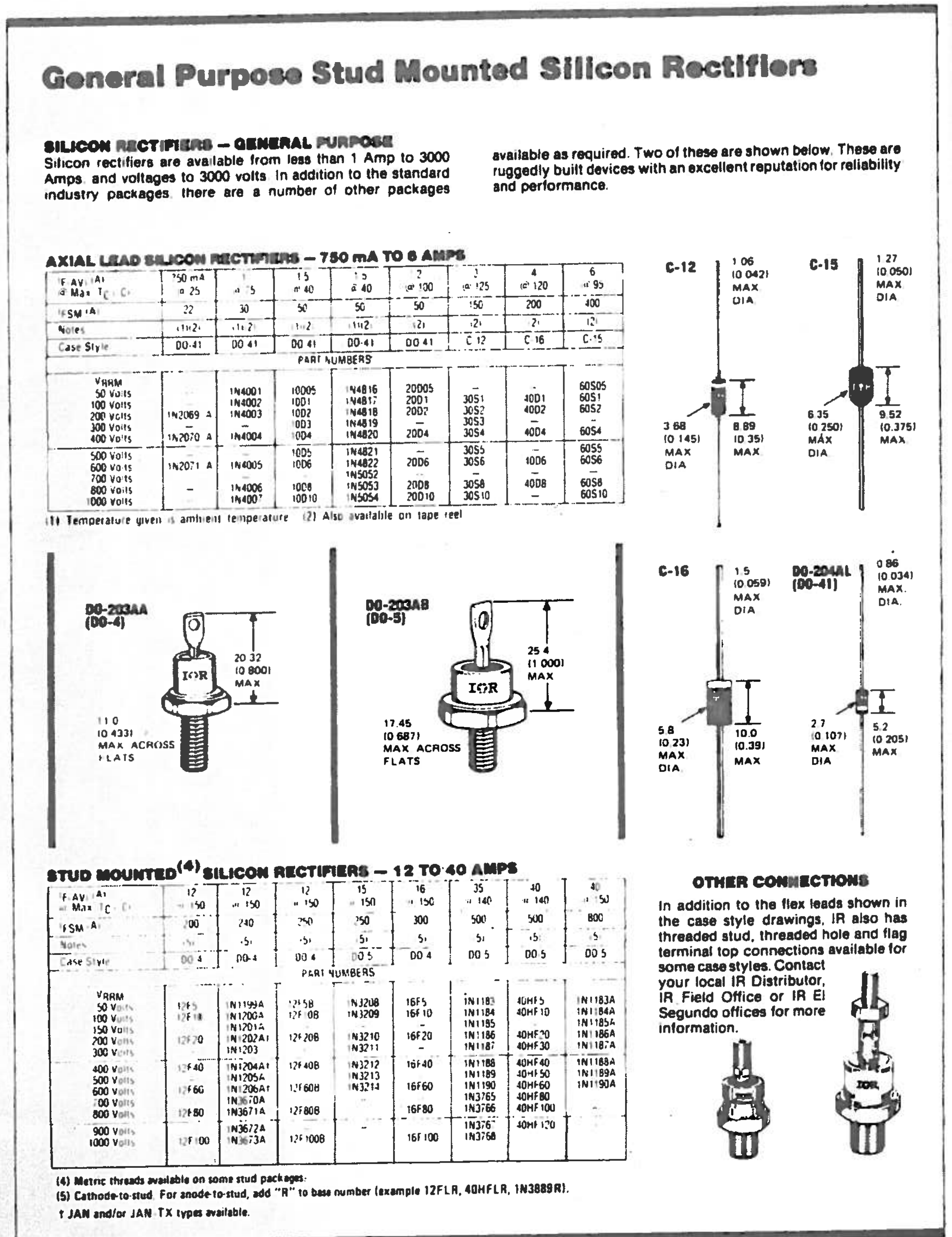


FIGURE 3–38(a) A typical rectifier data sheet (Courtesy of International Rectifier)

will need to perform a few calculations that will yield the required specifications and ratings for the power supply components.

Let us begin with the transformer. We will need to work backwards from the regulated output voltage, to the unregulated voltage, to the secondary voltage from the transformer. An important point to remember is that if a diode-bridge rectifier is to be used, the secondary

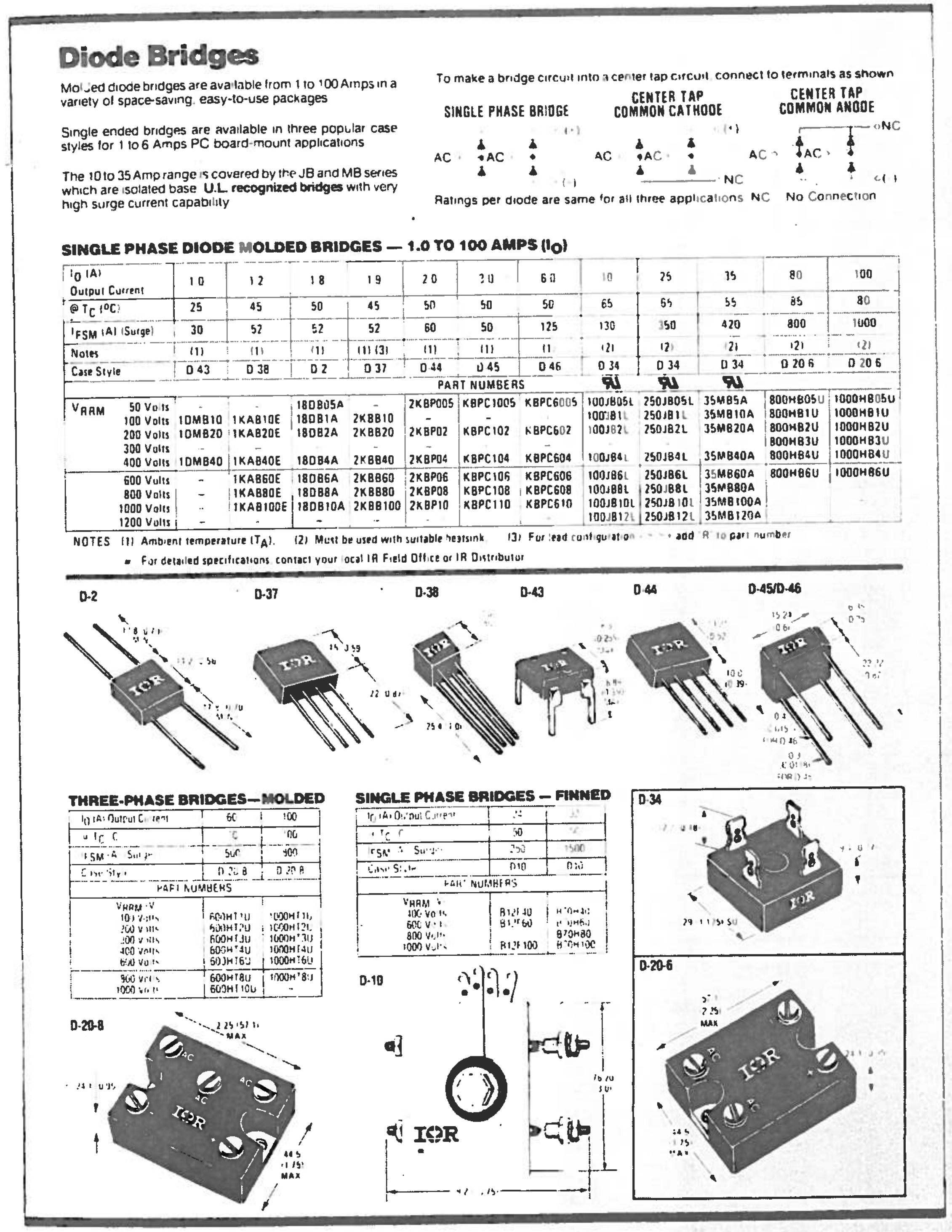


FIGURE 3–38(b) Diode bridge specifications (Courtesy of International Rectifier)

peak voltage from the transformer should be, in ballpark numbers, close to the required unregulated voltage. If a center-tapped transformer and two diodes are used, the secondary voltage must be twice as much. Remember that the filtering capacitor charges to the peak voltage of the rectified waveform.

Because the dc unregulated voltage has a ripple component, the peak voltage of the rectified waveform (V_{PR}) needs to be somewhat larger than the minimum required unregulated dc voltage. When a voltage regulator IC is used, the ripple factor does not have to be very low; a 10% figure would be adequate. Therefore, V_{PR} needs to be about 5% higher than the minimum unregulated dc voltage. We will also need to take into account one or two diode drops depending on whether we use a rectifier with center-tapped transformer or a diode bridge, respectively.

The current rating of both transformer and diodes is the same. The sum of all the load currents times a safety factor will determine the current rating. Additionally, the PIV rating of the diodes needs to be specified as well. Recall that the maximum reverse voltage per diode equals the peak voltage from the secondary. A safety factor can also be used for the PIV rating. In both cases, a safety factor of 1.5 to 2 is adequate.

For the capacitor value(s) and rating(s), we make use of the ripple voltage formula (equation 3–12) in terms of the load current. Again, if the power supply includes a regulator, a 10% ripple factor is acceptable. However, if a regulator is not required, the ripple factor should be less than 5%. The capacitor voltage should be somewhat larger than V_{PR}; a safety factor of 1.5 to 2 is also appropriate for capacitor voltage.

Finally, a fuse needs to be placed in series with one of the ac power lines to protect the power supply in case an excessive current develops anywhere in the circuit or the load. The power in the primary of the transformer is about the same as that in the secondary because the efficiency of commercial transformers is high. Therefore, the rms voltage-current product in the primary will equal the rms voltage-current product in the secondary. The fuse current rating should be about 50% higher than the calculated primary current. Additionally, if more than one regulator will be used, it would be a good idea to also protect the input to each regulator with a quick-acting fuse.

EXAMPLE 3–14

Design an experimenter's power supply that provides two regulated voltages: +12 V at 1 A and +5 V at 1 A.

Solution

We start by specifying the two regulators; the 7812 for the 12-V output, and the 7805 for the 5-V output. The 7812 requires a minimum unregulated input voltage of 14.6 V. Let us work with a target of 16 V.

Now we can determine the specs for the transformer. With a 10% ripple, V_{PR} needs to be 16.8 V, which is 5% above 16 V. If we choose to use a diode-bridge rectifier, then $16.8 = 1.41\ V_{rms} - 1.4$ V, from which $V_{rms} = 12.9$ V (secondary voltage). We can specify a 12-V transformer because the actual secondary voltage would be about 13 V to 14 V at normal loading. The transformer's current rating should be at least 2 A because the current from each regulator can be up to 1 A. However, it is not a good engineering practice to specify ratings based on strict minimum requirements; one should always use a safety margin. A rating of 2.5 or 3 A will do the job.

The filter capacitance value is determined by using equation 3–12 with $I_L = 2$A, $f_r = 120$ Hz, and $V_{PP} = 10\%$ of 16 V = 1.6 V. (We are using a 10% ripple factor.)

$$C = \frac{I_L}{f_r V_{PP}}$$

$$= \frac{2\text{ A}}{(120\text{ Hz})(1.6\text{ V})} = 10{,}400\ \mu\text{F}$$

The voltage rating should be at least the value of V_{PR} or, in this case, about 17 V. A capacitor with a voltage rating of 25 or 30 V is appropriate. The final capacitor specification is: Electrolytic type, 10,000 µF at 25 or 30 V.

Diode-bridge specification is based on the total load current and the reverse voltage to which the diodes will be exposed. As stated previously, the diode rating is the same as for the transformer: 2 or 2.5 A. The reverse voltage per diode is the peak voltage from the secondary or about 17 V. We will use a PIV rating of 50 V, which is the lowest typically available.

The fuse is finally specified according to the current in the primary which can be obtained from equating primary and secondary powers, that is,

$$V_{pri}\, I_{pri} = V_{sec}\, I_{sec}$$

which yields

$$I_{pri} = \frac{V_{sec}\, I_{sec}}{V_{pri}}$$

and

$$I_{pri} = \frac{(2\text{ A})(12\text{ V})}{120\text{ V}} = 200\text{ mA}$$

A 250 mA, slow-blow type would be a good choice for the fuse. Slow-blow specification is necessary because when the power is first turned on, the initial current is much larger than the normal operating current. Additionally, the fuse should also protect the transformer if its maximum rating is exceeded. Therefore, the current rating of the fuse should not exceed the value of the primary current that results at the maximum rated secondary current. In our case, for example, if we use a 12–V, 3–A transformer, the primary current at the rated secondary current would be

$$I_{pri} = \frac{(3\text{ A})(12\text{ V})}{120\text{ V}} = 300\text{ mA}$$

The rating of the fuse must not exceed this value.

3–8 MULTISIM EXERCISE

Observing on the Oscilloscope the Filtered Output Voltage and the Diode Current in a Half-Wave Rectifier

Figure 3–39 shows a half-wave rectifier with capacitive filter and a resistive load. Notice that a 1-Ω resistor has been added in series with the ac voltage source to sense the diode current and display it on the oscilloscope. The resistor must be on the ground side because the oscilloscope must be grounded.

Before you start the simulation, double-click on the oscilloscope and set it up to 5 ms/div for the time axis, 1 V/div for channel A, and 100 V/div for channel B. Once the simulation is running, pause it and observe the waveform from channel A, which represents the diode current. Because the sensing resistor has a value of 1 Ω, the current will be numerically identical to the displayed voltage. Note that the current peaks reach almost 2 amperes. The current peaks appear negative on the oscilloscope because of the polarity of the voltage drop according to the direction of the diode current. Notice also that current flows through the diode only during the recharge of the capacitor.

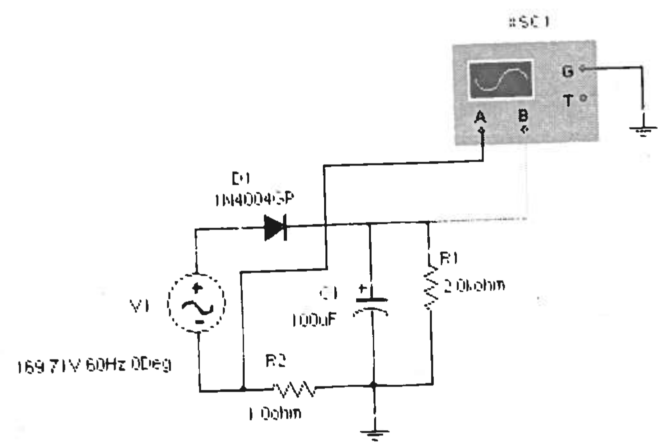


FIGURE 3-39 Half-wave rectifier with oscilloscope connected to observe diode current and output voltage

SUMMARY

This chapter has presented the use of diodes in circuits, particularly in rectifiers for basic power supplies. At the end of this chapter, the student should have an understanding of the following concepts:

- Diodes are used for allowing current to flow in only one direction.
- Diodes are an essential part in all power supplies.
- Rectified waveforms can be full-wave or half-wave.
- Full-wave rectification can be done with four diodes and an ac source, or with two diodes and a center-tapped transformer.
- Capacitive filtering substantially reduces the pulsating character of a rectified waveform.
- Zener diodes and special integrated circuits provide voltage regulation.

EXERCISES

SECTION 3-2

The Diode as a Nonlinear Device

3-1. Make a sketch of the *I-V* characteristic curve for a 10-kΩ resistor when current *I* is plotted along the vertical axis and voltage *V* along the horizontal axis. What is the slope of the characteristic? Be certain to include units in your answer.

3-2. Make a sketch of the *I-V* characteristic curve for a diode with $I_s = 0.02$ pA for V_D values from zero to 0.7 V. Use the approximation

$$I_D = I_s e^{V_D/V_T}$$

What is the slope of a line tangent to the curve at $I_D = 2$ mA?

SECTION 3-3

ac and dc Resistance

3-3. Using the diode *I-V* characteristic shown in Figure 3-40, find (graphically) the approximate ac resistance when the current in the diode is 0.1 mA. Repeat when the voltage across it is 0.64 V. Is the diode silicon or germanium?

3-4. Using the diode *I-V* characteristic shown in Figure 3-40, find (graphically) the approximate value of the dynamic resistance when the current in the diode is 0.2 mA. Repeat when the voltage across the diode is 0.62 V. What is the approximate maximum knee current?

3-5. Find the dc resistance of the diode at each point specified in Exercise 3-3.

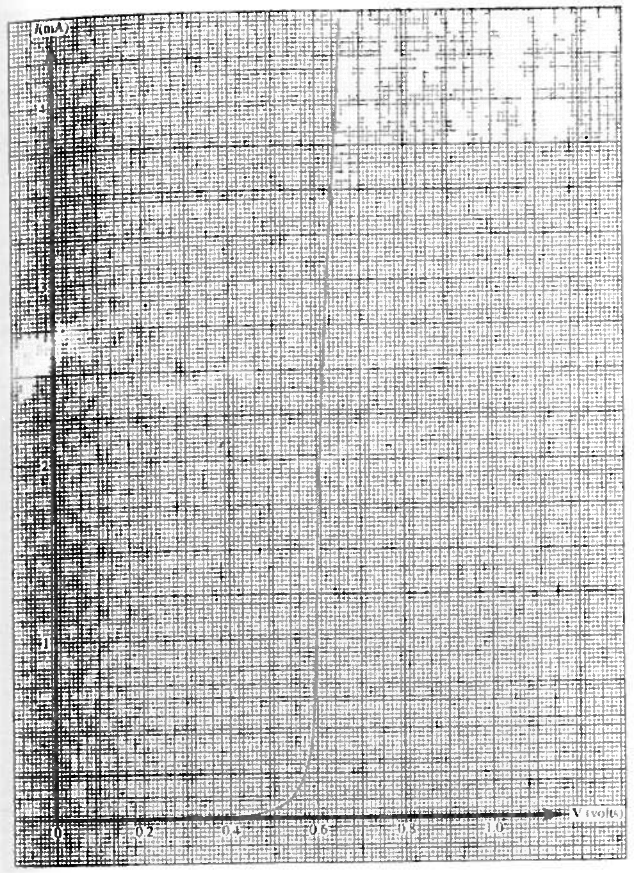


FIGURE 3-40 (Exercises 3-3 and 3-4).

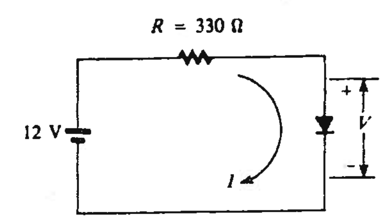


FIGURE 3-41 (Exercise 3-12)

3-6. Find the static resistance of the diode at each point specified in Exercise 3-4.

3-7. Neglecting bulk resistance, use equation 3-6 to find the approximate ac resistance of the diode at each point specified in Exercise 3-3.

3-8. Assume that the bulk resistance of the diode whose *I-V* characteristic is shown in Figure 3-41 is 0.1 Ω when the current is greater than 1.5 mA and 0.5 Ω when the current is less than 1.5 mA. Use equation 3-6 to find the approximate dynamic resistance of the diode at each point specified in Exercise 3-4.

3-9. A certain diode conducts a current of 440 nA from cathode to anode when the reverse-biasing voltage across it is 8 V. What is the diode's dc resistance under these conditions?

3-10. When the reverse-biasing voltage in Exercise 3-9 is increased to 24 V, the reverse current increases to 1.20 µA. What is its dc resistance in this case?

3-11. In the test circuit shown in Figure 3-3, a diode voltage of 0.69 V was measured when the diode current was 163 mA.

(a) What is the dc resistance of the diode at $V_D = 0.69$ V?

(b) What is the ac resistance of the diode when the voltage across it changes from 0.68 V to 0.69 V?

3-12. In the circuit shown in Figure 3-41, the current *I* is 34.28 mA. What is the voltage drop across the diode? What is its dc resistance?

3-13. Repeat Exercise 3-12 if the resistor *R* is 220 Ω and the current *I* is 51.63 mA.

SECTION 3-4

Analysis of dc Circuits Containing Diodes

3-14. Determine the currents I_1 and I_2 in Figure 3-42. Assume silicon diodes.

3-15. Repeat Problem 3-14 when diode D_1 is reversed.

3-16. The voltage V_S in Figure 3-43 can be varied between zero and 20 V. Assuming the diodes behave as shown in Figure 3-13(b):

(a) Determine the voltage levels of V_S at which D_1 and D_2 begin conducting.

(b) Find the currents through each diode when V_S reaches 20 V.

3-17. Find the current in each diode in the circuit of Figure 3-44. Assume diode drops of 0.7 V.

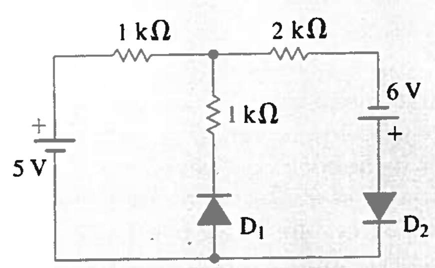


FIGURE 3-42 (Exercise 3-14)

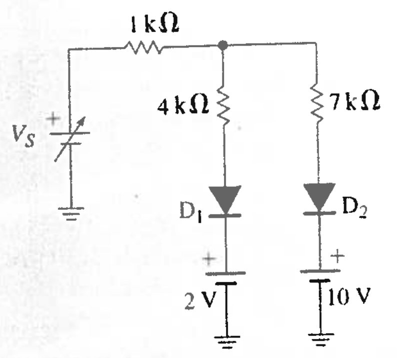


FIGURE 3–43 (Exercise 3-16)

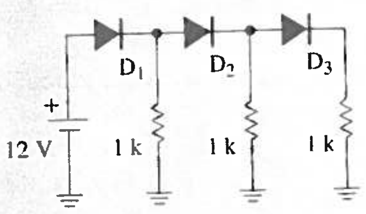


FIGURE 3–44 (Exercise 3-17)

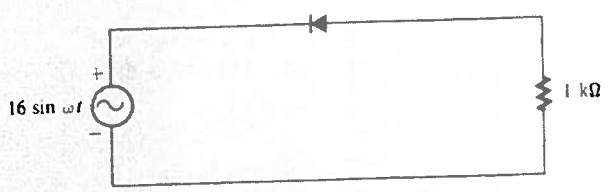


FIGURE 3–45 (Exercise 3-19)

SECTION 3–5
Elementary Power Supplies

3-18. In the circuit shown in Figure 3–15, the 1.5-kΩ resistor is replaced with a 2.2-kΩ resistor. Assume that the silicon diode has a characteristic curve like that shown in Figure 3–13(b). If $e(t) = 2 \sin \omega t$, find the peak value of the current $i(t)$ and the voltage $v_R(t)$ across the resistor. Sketch the waveforms for $e(t)$, $i(t)$, and $v_R(t)$.

3-19. The silicon diode in Figure 3–45 has a characteristic curve like that shown in Figure 3–13(b). Find the peak values of the current $i(t)$ and the voltage $v_R(t)$ across the resistor. Sketch the waveforms for $e(t)$, $i(t)$, and $v_R(t)$.

3-20. What peak-to-peak sinusoidal voltage must be connected to a half-wave rectifier if the rectified waveform is to have a dc value of 6 V? Assume that the forward drop across the diode is 0.7 V.

3-21. What should be the rms voltage of a sinusoidal wave connected to a full-wave rectifier if the rectified waveform is to have a dc value of 50 V? Neglect diode voltage drops.

3-22. The half-wave rectifier in Figure 3–19 has a 250-μF filter capacitor and a 1.5-kΩ load. The ac source is 120 V rms with frequency 60 Hz. The voltage drop across the silicon diode is 0.7 V. Assuming light loading, find

(a) the dc value of the load voltage;

(b) the peak-to-peak value of the ripple voltage.

3-23. The half-wave rectifier in Exercise 3–22 is replaced by a silicon full-wave rectifier, and a second 250–μF capacitor is connected in parallel with the filter capacitor. Assume light loading and do not neglect the voltage drop across the diodes. Find

(a) the dc value of the load voltage;

(b) the peak-to-peak value of the ripple voltage.

(c) If the load resistance is decreased by a factor of 2, determine (without recalculating) the approximate factor by which the ripple voltage is changed.

3-24. The primary voltage on the transformer shown in Figure 3–46 is 120 V rms and R_L = 10 Ω. Neglecting the forward voltage drops across the diodes, find

(a) the turns ratio $N_P : N_S$, if the average current in the resistor must be 1.5 A;

(b) the average power dissipated in the resistor, under the conditions of (a); and

(c) the maximum PIV rating required for the diodes, under the conditions of (a).

3-25. The primary voltage on the transformer in Figure 3–46 is 120 V rms and $N_P : N_S$ = 15:1. Diode voltage drops are 0.7 V.

(a) What should be the value of R_L if the average current in R_L must be 0.5 A?

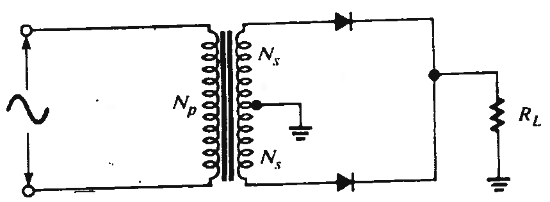


FIGURE 3–46 (Exercises 3-24 and 3-25)

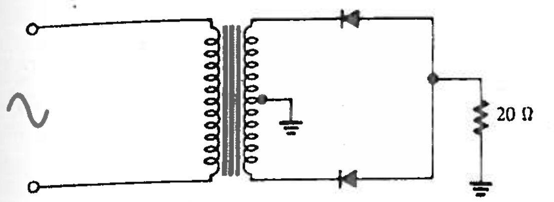


FIGURE 3–47 (Exercise 3-26)

(b) What power is dissipated in R_L under the conditions of (a)?

(c) What minimum PIV rating is required for the diodes under the conditions of (a)?

3-26. The secondary voltage on the transformer in Figure 3-47 is 30 VCT rms at 50 Hz. The diode voltage drops are 0.7 V. Sketch the waveforms of the voltage across and current through the 20-Ω resistor. Label peak values and the time points where the waveforms go to 0.

3-27. Each of the diodes in Figure 3–48 has a forward voltage drop of 0.7 V. Find

(a) the average voltage across R_L;

(b) the average power dissipated in the 1-Ω resistor; and

(c) the minimum PIV rating required for the diodes.

3-28. Repeat Exercise 3–27 if R_L is changed to 5 Ω and the transformer turns ratio is changed to 1:1.5.

3-29. Sketch the waveform of the voltage v_L in the circuit shown in Figure 3–49. Include the ripple and show the value of its period on the sketch. Also show the value of V_{PR}. Neglect the forward drop across the diode.

3-30. What is the percent ripple of a full-wave–rectified waveform having a peak value 75 V and frequency 120 Hz if C = 220 μF and I_L = 80 mA? What is the percent ripple if the frequency is halved?

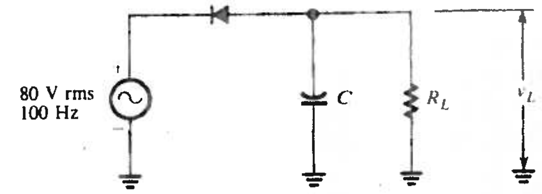


FIGURE 3–49 (Exercise 3-29)

3-31. A half-wave rectifier is operated from a 60-Hz line and has a 1000-μF filter capacitance connected across it. What is the minimum value of load resistance that can be connected across the capacitor if the percent ripple cannot exceed 5%?

3-32. A full-wave rectifier is operated from a 60-Hz, 50-V-rms source. It has a 500-μF filter capacitor and a 750-Ω load. Find

(a) the average value of the load voltage;

(b) the peak-to-peak ripple voltage; and

(c) the percent ripple.

3-33. A half-wave rectifier has a 1000-μF filter capacitor and a 500-Ω load. It is operated from a 60-Hz, 120-V-rms source. It takes 1 ms for the capacitor to recharge during each input cycle. For what minimum value of repetitive surge current should the diode be rated?

3-34. Repeat Exercise 3–33 if the rectifier is full-wave and the capacitor takes 0.5 ms to recharge.

3-35. Assuming negligible ripple, find the average current in the 100-kΩ resistor in Figure 3–50.

3-36. The transformer shown in Figure 3–51 has a *tapped secondary* each portion of the secondary winding having the number of turns shown. Assuming that the primary voltage is that shown in the figure, design two separate circuits that can be used with the transformer to obtain an (unloaded) dc

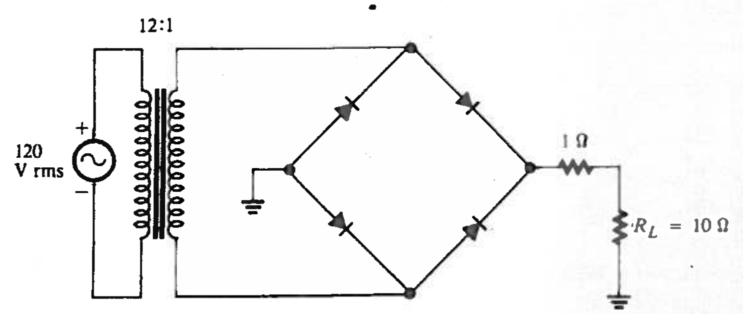


FIGURE 3–48 (Exercise 3-27)

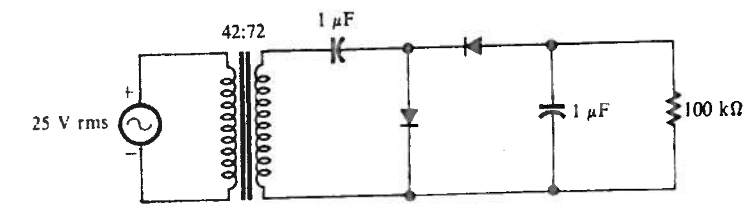


FIGURE 3–50 (Exercise 3-35)

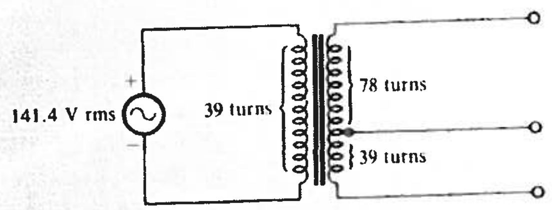


FIGURE 3–51 (Exercise 3-36)

voltage of 1200 V. It is not necessary to specify capacitor sizes. What minimum PIV ratings should the diodes in each design have?

SECTION 3–6

Elementary Voltage Regulation

3–37. In the circuit shown in Figure 3–52, the zener diode has a reverse breakdown voltage of 12 V. $R_S = 50\ \Omega$, $V_S = 20$ V, and R_L can vary from 100 Ω to 200 Ω. Assuming that the zener diode remains in breakdown, find

(a) the minimum and maximum current in the zener diode;

(b) the minimum and maximum power dissipated in the diode; and

(c) the minimum rated power dissipation that R_S should have.

3–38. Repeat Exercise 3–37 if, in addition to the variation in R_L, V_S can vary from 19 V to 30 V.

3–39. The 6-V zener diode in Figure 3–53 has a maximum rated power dissipation of 0.5 W. Its reverse current must be at least 5 mA to keep it in breakdown. Find a suitable value for R_S if V_S can vary from 8 V to 12 V and R_L can vary from 500 Ω to 1 kΩ.

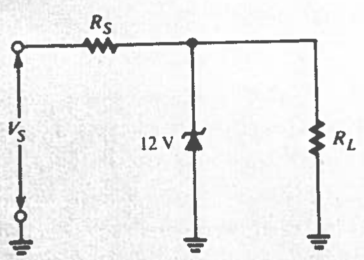


FIGURE 3–52 (Exercises 3-37 and 3-38)

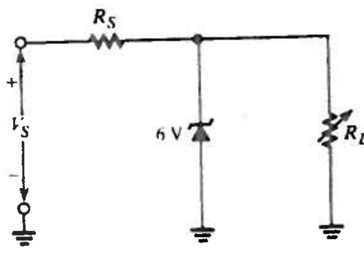


FIGURE 3–53 (Exercise 3-39)

3–40. (a) If R_S in Exercise 3–39 is set to its maximum permissible value, what is the maximum permissible value of V_S?

(b) If R_S in Exercise 3–39 is set equal to its minimum permissible value, what is the minimum permissible value of R_L?

3–41. A zener diode has a breakdown voltage of 12 V at 25°C and a temperature coefficient of +0.5 mV/°C.

(a) Design a temperature-stabilizing circuit using silicon diodes that have temperature coefficients of −0.21 mV/°C. The forward drop across each diode at 25°C is 0.68 V.

(b) Find the voltage across the stabilized network at 25°C and at 75°C.

(c) Find the temperature stability of the stabilized network.

3–42. A zener diode has a breakdown voltage of 15.1 V at 25°C. It has a temperature coefficient of +0.78 mV/°C and is to be operated between 25°C and 100°C. It is to be temperature stabilized in such a way that the voltage across the network is never less than its value at 25°C.

(a) Design a temperature-stabilizing network using silicon diodes whose temperature coefficients are −0.2 mV/°C. The forward drop across each diode at 25°C is 0.65 V.

(b) What is the maximum voltage across the stabilized network?

3–43. Following is a set of measurements that were made on the voltage across and current through a zener diode:

I_z(mA)	V_z(volts)
0.5	30.1
1.0	30.15
2.0	30.25
3.5	30.37
6	30.56
8	30.68
10	30.80
30	31.90
40	32.40
90	34.00

(a) Find the approximate zener impedance over the range from $I_Z = 3.5$ mA to $I_Z = 10$ mA.

(b) Show that the zener impedance decreases with increasing current.

3–44. The breakdown voltage of a zener diode when it is conducting 2.5 mA is 7.5 V. If the voltage must not increase more than 10% when the current increases 50%, what maximum impedance can the diode have?

SECTION 3–7

Diode Types, Ratings, and Specifications

3–45. In the circuit shown in Example 3–13 (Figure 3–36), suppose the load resistor R is changed to 47 Ω. What then is the least expensive of the diodes listed in the example that can be used in this application?

3–46. In the circuit shown in Example 3–13 (Figure 3–36), suppose the ac voltage is 100 V rms and the load resistor is changed to 68 Ω. What then is the least expensive of the diodes listed in the example that can be used in this application?

3–47. A small-signal diode is to be used in an application where it will be subjected to a reverse voltage of 35 V. It must conduct a forward current of 0.01 A when the forward-biasing voltage is 1.0 V. The reverse current must not exceed 30 nA when the reverse voltage is 30 V. Select a diode type number from Figure 3–37 that meets these requirements.

3–48. A silicon diode is to be used in an application where it will be subjected to a reverse-biasing voltage of 85 V. The forward current will not exceed 100 mA, but it must have a 0.5-W power dissipation rating. Select a diode type number from Figure 3–37 that meets these requirements.

3–49. A rectifier diode is to be used in a power supply design where it must repeatedly withstand sine wave reverse voltages of 250 V rms and must conduct 0.6 A (average) of forward current. The forward surge current through the diode when the supply is first turned on will be 25 A. It is estimated that the diode case temperature (T_C) will be 30°C. Select a diode type number from Figure 3–38 that meets these requirements.

3–50. A rectifier diode is to be used in a large power supply where it must be capable of withstanding repeated reverse voltages of 450 peak volts. The forward current in the diode will average 13.5 A. Select a diode type number from Figure 3–38 that meets these requirements.

3–51. A full-wave bridge is to be connected to a 240-V-rms power line. The output will be filtered and will supply an average voltage of 150 V to a 50-Ω load. The worst-case current that will flow through the bridge when power is first applied is 20 times the average load current. Using the International Rectifier specifications in Figure 3–38(b), select a bridge (give its part number) that can be used for this application.

PSPICE EXERCISES

3–52. Simulate Problem 3–14 using PSpice. Use the part DIN4002 in the "Eval" library for both diodes. Hint: Include in your circuit file the .OP statement in order to obtain a report on the diode currents in the output file.

3–53. Simulate Problem 3–16 using PSpice with the voltage source V_S swept from zero to 20 V. Plot both diode currents versus V_S. Hint: Use .DC analysis.